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NOTICE

Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal,* should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

Among papers to appear in forthcoming issues of the *Journal* are the following:

Analcime in the Chinle formation of Utah correlative with the Popo Agie of Wyoming. By W. D. Keller.

Illite and montmorillonite in green sedimentary rocks. By W. D. Keller.

Evidence of biochemical heating in Lake Mead mud. By C. E. ZoBell, F. D. Sisler, and C. H. Oppenheimer.

A new roundness scale for sedimentary particles. By M. C. Powers.

Rafted pebbles from the deep ocean off Baja California. By G. A. Shumway.

Para-ripples in limestone, with special reference to occurrence in the Mississippian Boone formation. By V. O. Tansey.

Origin of the tufa deposits in Mono Lake, California. By J. R. Dunn.

A method for the size analysis of sand on a number frequency basis. By A. W. Marschner.

Correlation of the tills of northeastern Ohio by size analysis. By V C. Shepps.

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FIGS. 1–6, DECEMBER, 1952

IMBRICATION AND INITIAL DIP IN A KEWEENAWAN CONGLOMERATE BED

WALTER S. WHITE
United States Geological Survey

ABSTRACT

The source of rhyolitic debris composing conglomerate beds in the Keweenawan lava series of northern Michigan has not been firmly established heretofore. Statistical measurement of imbrication in one bed, the Houghton conglomerate, indicates that the depositing stream flowed from southeast to northwest. The average inclination of pebbles, corrected for the present dip of the bed, is 8° SE. This is compared with the inclinations of imbricated pebbles measured by Krumbein in California flood gravels. In addition, many pebbles in the Houghton conglomerate are inclined at about 40° to bedding; it is suggested that these pebbles may have slumped into small scour craters.

INTRODUCTION

A number of thin, stream-deposited conglomerate beds are interlayered with the Keweenawan lava flows of northern Michigan. Geologists have not been in general agreement on the source of the rhyolitic material that composes most of the pebbles, yet knowledge of the direction in which the ancient streams flowed is essential to a reconstruction of the physiography of the Keweenawan basin of deposition. This reconstruction, in turn, may prove helpful or even necessary to the geologic search for new copper deposits. The major copper deposits of the lava series are almost certainly related in part to primary permeability in conglomerate beds and fragmental flow tops (Butler and Burbank, 1929, pp. 115–116; Broderick, Hohl, and Eidemiller, 1946, pp. 706–709); this permeability presumably varied with factors such as slope and distance from source, which are related to the ancient topography of the basin.

As pointed out by Butler and Burbank (1929, pp. 19–20) in a concise statement of the problem, the source must have lain outside the northeast-trending belt in which the lavas are now exposed (fig. 1), and therefore must be either south to southeast or north to northwest of the copper district. Study of imbrication and initial dip in the Houghton conglomerate at the Allouez No. 3 shaft of the Calumet & Hecla Consolidated Copper Co. (fig. 1) indicates a southern source for that bed. This paper presents the evidence for this conclusion, and describes an additional sedimentary phenomenon, revealed by the study, that might have general usefulness as a geologic tool. Many pebbles in the Houghton conglomerate are inclined at about 40° to the bedding; it is suggested that these pebbles may have slumped into scour craters formed in the lee of cobbles or boulders.

The measurements on which the study is based were made in two days with the assistance, both in measuring and in recording, of James C. Wright, a fellow member of the U. S. Geological Survey party studying the Michigan copper district. The writer is indebted to the management of the Calumet & Hecla Consolidated Copper Co. for permission to make the necessary underground observations, and in particular to Dr. T. M. Broderick, Chief Geologist of the company, for use of the excellent geologic records in the file of his Geological Department. The presentation has been much improved by the thoughtful criticism of C. E. Dutton, F. J. Pettijohn, W. W. Rubey, E. S. Davidson, and J. C. Wright.

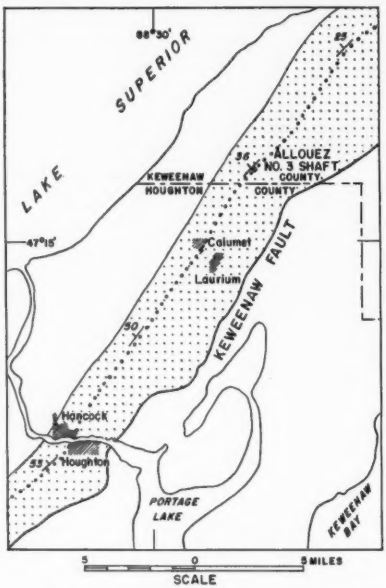

FIG. 1.—Part of Michigan copper district. Line of small circles shows approximate trace of the horizon of the Houghton conglomerate and strike and dip symbols show its attitude. Stippled area is underlain by Portage Lake lava series.

GENERAL GEOLOGY

The geology of the Michigan copper district has been described in great detail (Butler and Burbank, 1929, particularly pp. 16–26; Broderick, Hohl, and Eidemiller, 1946, particularly pp. 679–683; Lane, 1911, pp. 15–48) and is only summarized here. The rocks exposed in the vicinity of the Allouez No. 3 shaft consist of 11,000 feet of mafic lava flows, recently renamed the Portage Lake lava series (White, Cornwall, and Swanson, 1952), overlain by 4,000 feet of conglomerate, the Copper Harbor conglomerate (Lane, 1911, pp. 37–39). The Portage Lake lava series contains a few thin conglomerate beds, perhaps aggregating 3 per cent of the total thickness, and the Copper Harbor conglomerate contains a few lava flows. Younger shales and sandstones of the Keweenawan series overlie the Copper Harbor conglomerate. In the vicinity of the Allouez No. 3 shaft, the exposed section is bounded at the base by the Keweenaw fault (fig. 1), along which the lava flows are thrust over the much younger Jacobsville sandstone, of probable uppermost Keweenawan age.

Throughout the main part of the copper district the rocks northwest of the Keweenaw fault strike northeast or east and dip northwestward or northward toward Lake Superior. The angle of dip generally lies between 25° and 75°.

THE HOUGHTON CONGLOMERATE

The Houghton conglomerate is one of about 20 sedimentary beds included within the Portage Lake lava series. At the Allouez No. 3 shaft the conglomerate lies about 3,750 feet stratigraphically below the top of the series. The bed is separated by 500 feet of mafic lava flows from the next higher conglomerate bed, the Allouez, and by 850 feet of lava flows from the next lower, the Calumet & Hecla.

At the Allouez No. 3 shaft, the rocks strike N. 45° E. and dip 36° NW. The conglomerate bed at this shaft is a lenticular body, 1,000 to 1,800 feet wide measured parallel to the strike, at least 4,000 feet long in the direction of dip, and ranging in thickness from less than a foot at its lateral margins to as much as 25 feet along its principal axis. Down to 1,600 feet on the incline, the long axis of the lens trends N. 45° W., parallel to the dip of the bed. Diamond drilling suggests that the long axis may curve northward below this level to give an average axial trend of N. 25°–35° W. for the lens as a whole to a depth of 4,000 feet on the incline. The lens generally widens and thickens down the dip. In shape and orientation, it is similar to but much smaller than the lens of the Calumet & Hecla conglomerate that was mined at Calumet (Butler and Burbank, 1929, pp. 182–190, pl. 38).

Away from the area of the Allouez shaft, the top of the flow that underlies the Houghton conglomerate can be readily identified for many miles (fig. 1) by its stratigraphic position relative to other flows and conglomerate beds, and by the common presence of fine detrital material in the interstices of its amygdaloidal top. But the Houghton conglomerate bed itself is absent in 70 per cent of the drill holes and crosscuts that intersect its stratigraphic horizon.

The sand, pebbles, and boulders that constitute the Houghton conglomerate, as well as most other conglomerate beds in the region, are dominantly red rhyolite, generally assumed to be Keweenawan in age and penecontemporaneous with the mafic lavas. Locally 30 to 40 per cent of the pebbles and boulders are massive or amygdaloidal mafic lava, but 10 to 20 per cent is a more common proportion. Fragments of pre-Keweenawan rock, such as quartzite, iron-formation, or granite, have not been noted in the Houghton conglomerate. The matrix of the conglomerate is medium to coarse sand of the same general composition as the larger fragments. A detrital layer of mafic material from the subjacent flow, described by Butler and Burbank (1929, pp. 20–21) as "amygdaloidal conglomerate," locally underlies the rhyolite conglomerate.

The size of fragments in the rhyolite conglomerate is varied, both at different stratigraphic levels within the bed at any one place, and from place to place. Boulders of mafic lava 3 feet across were noted in both deep (2,000 feet down the dip) and shallow mine workings, and sand layers a foot or more in thickness are common throughout the lens. In the mine as a whole, 50 per cent or more of the material seems to be greater than 1 inch in maximum diameter, and in several places the most abundant material by volume is 4 inches or more in diameter. These estimates are based on visual inspection, as no detailed measurements of size distribution have been made.

Rounding and sphericity, likewise, have not been studied quantitatively. Much of the coarse rhyolitic material shows a high degree of rounding; only a small number of the larger cobbles and boulders have pronounced corners, and smooth ovoid or ellipsoidal forms are common. The finer fragments of rhyolite (less than $\frac{1}{4}$ inch), on the other hand, are notably angular. The mafic boulders are generally much more poorly rounded than the rhyolitic, and some have conspicuously squared corners. Sphericity, also, seems to be best developed in the rhyolite fragments. In the conglomerate as a whole, the percentage of nearly equidimensional pebbles, cobbles, and boulders is very high; only a few of the fragments on the many rock faces examined were sufficiently elongate to be of optimum value in a study of imbrication.

The conglomerate is completely lithified and more commonly breaks across pebbles than around them. Many tiny slips, generally more or less parallel to bedding, cut the rock, and the displacement of pebble boundaries on most of these slips indicates upward, or reverse, movement of the hanging wall. There is no evidence of any other type of deformation in the rock, except some granulation of the finer-grained material of the matrix.

The conglomerate bed, at many places, contains layers and lenses of sandstone from less than an inch to as much as 2 feet in thickness. Foreset lamination was observed in two such lenses; the laminae dip 15°–20° more steeply toward the northwest than the present dip of the lenses. The individual lenses and layers of sandstone likewise tend to dip more steeply than the dip of the conglomerate bed as a whole. The average dip of 12 sandstone layers is 39° NW., 3° steeper than the dip of the conglomerate bed; the maximum observed dip is 46° (three different places), and no dip less than 35° was found. These dips suggest a foreset arrangement of the sandstone layers and lenses within the conglomerate bed as a whole. All these observations

are taken as evidence that original stream flow was in the direction of the present dip of the beds, that is, from southeast to northwest.

Exposures in the Allouez No. 3 Shaft

The Allouez No. 3 shaft is an inclined shaft in the Houghton conglomerate. It was started in 1943 and now extends more than 2,000 feet down the dip. Good exposures are less common than might be expected. As will be indicated below, only vertical faces oriented more or less normal to the strike of the bed are suitable for the measurements that were made. Such faces are found in the shaft, in crosscuts, in chute gates below stopes, along the side walls of stopes and raises, and at the ends of drifts. The principal obstacles to examination of the rocks are muddy walls, a tendency of the rock to break on mineralized joints that conceal the fresh rock, and battering by scrapers and other equipment. Most workings more than 100 feet from the shaft cannot be safely examined in the upper 1,500 feet of the mine because of extensive caving. All reasonably safe places in the mine were searched.

IMBRICATION

A study of imbrication offered the most hope for conclusive evidence on the direction of source. The 2,000-foot length of stream course available for study here is much too short for methods based on comparison of properties like size and rounding from place to place.

Krumbein (1940, 1942) proved the existence of imbrication in flood gravels of San Gabriel Canyon and Arroyo Seco, Los Angeles County, California, by measuring the attitude in three dimensions of the long axes of a large number of pebbles. At most localities, the long axes of pebbles, plotted on a polar diagram, show a definite tendency to be inclined slightly upstream (Krumbein, 1940, figs. 3 and 7; 1942, figs. 15 and 16). The degree of lithification prevents a comparable three-dimensional orientation study of the Houghton conglomerate, as very few pebbles can be plucked from their matrix. Therefore another type of measurement was made.

The information sought here is merely evidence for either an up-dip or down-dip direction of stream flow, as it can reasonably be assumed that the flow was more or less parallel to the long axis of the conglomerate lens. Because of the fortunate circumstance that this long axis is essentially parallel to the dip of bedding, imbrication, if present, should be almost perfectly revealed by comparing the average dip of elongate pebbles with the dip of the conglomerate bed. The dip of the apparent long axes of individual pebbles was therefore measured on all accessible vertical faces oriented more or less normal to the strike of the bed.

As the direction of imbrication is of more immediate concern than the extent of imbrication, and as the flattest pebbles should most conclusively reveal imbrication, if present, pebbles with ratios of less than 1.5:1 for apparent length to apparent breadth were generally ignored. Similarly, pebbles with odd shapes that might tilt in any direction, particularly those tending to be triangular, were disregarded, even though they might technically have elongations of 1.5:1 or more. As a result of this high selectivity and the scarcity of clean faces with the proper orientation in the mine, only 388 pebbles in the whole mine were found suitable for measurement; they are distributed fairly evenly from about 800 to 2,000 feet down the dip.

The location, dip of apparent long axis in section, size class based on largest visible dimension, and lithology of each pebble were noted. The lithology seems to have no significance. The size classes recognized are the following, in inches: less than 2, 2 to 4, 4 to 8, more than 8. In addition, 24 of these same pebbles that had lengths three or more times their widths were noted as being distinctly slablike.

The recorded data are tabulated in figure 2. Each pebble classified as a slab

is also recorded in its size class. Relatively smooth curves are obtained by graphing a moving total of the number of pebbles within a 15° range. Moving-total curves for each size class, a curve for the slabs, and a curve for all pebbles are presented in figure 3.

The smallest material shows no discernible tendency toward imbrication; the mean inclination, corrected for present dip (36° NW.), is 0.5° NW. Pebbles 2 to 4 inches long, pebbles more than 8 inches long, and the slabs have a notable preferred inclination to the southeast after correction for the dip of the conglomerate bed. The mean inclination (corrected for dip) of the pebbles 2 to 4 inches long and of the slabs is 8° SE.; that of the pebbles more than 8 inches long is 13° SE. The most common inclination in each of these groups is likewise notably southeastward.

The peak of the moving-total curve for pebbles 4 to 8 inches long lies close to the horizontal (corrected for dip), but the mean inclination is 8° SE., like the mean for all pebbles. The reason for the marked asymmetry of this curve is not known.

The dip data, after correction for the present dip of bedding (36° NW.), show consistent evidence of an average southeastward inclination of all but the smallest pebbles. The angle of inclination is somewhat smaller than the average of 15°–30° for fluviatile gravel cited by Pettijohn (1949, p. 203) from the work of Cailleux. But comparable inclinations were found by Krumbein in San Gabriel Canyon and Arroyo Seco, California. Krumbein (1940, p. 652, and 1942, p. 1387) gives the orientation of pebbles in 12 samples of 100 pebbles each from flood sediments at these localities. The orientation is given in three dimensions on polar coordinate charts but can be referred to a section parallel to the stream, for purposes of comparison with the data on the Houghton conglomerate, on the basis of either of two assumptions.

First, it may be assumed that, in the selection of inequidimensional pebbles at

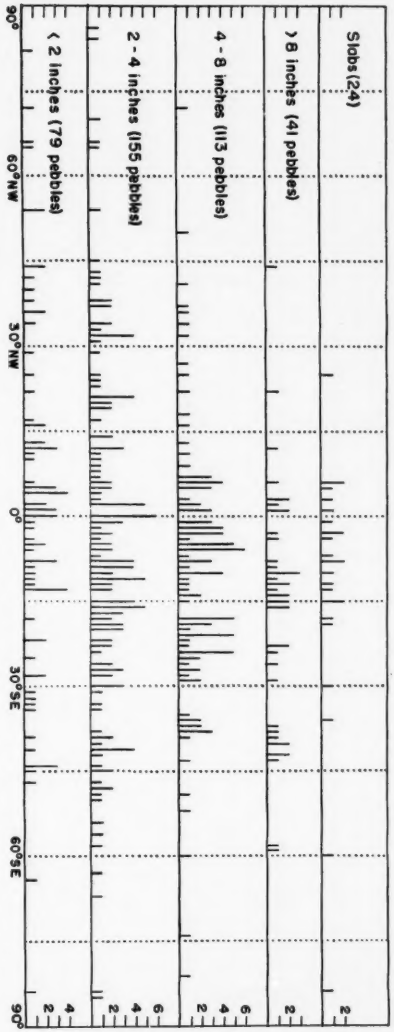

FIG. 2.—Inclination of apparent long axes of individual pebbles in the Houghton conglomerate, Allouez No. 3 shaft, measured in a vertical section striking N. 45° W. ±15°. Present dip of bed (36° NW.) is taken as zero. Length of bar indicates number of pebbles (scale at bottom) in each 1° class (scale at side).

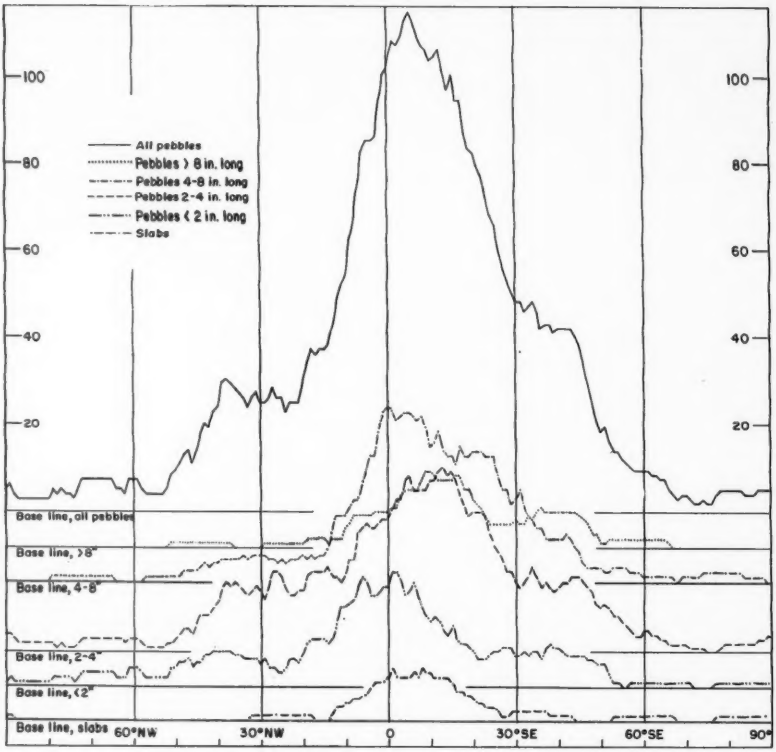

FIG. 3.—Frequency of pebble inclinations, Allouez No. 3 shaft. Data of figure 2 expressed as 15° moving totals.

the Allouez No. 3 shaft, most of the pebbles with true long axes notably athwart the dip direction would have been disregarded. In an approach to this type of selection, a tabulation was made of the true dips of all of Krumbein's pebbles that have azimuths within 30° of the recorded stream direction. Two curves prepared on this basis, one for San Gabriel Canyon (A) and one for Arroyo Seco (B), are shown in figure 4. The vertical scale gives the percentage of the total pebbles in each 5°-dip class, and each curve plots a moving average of three points. The San Gabriel pebbles show a greater spread and have a mean upstream inclination of $13\frac{1}{2}°$, in contrast with the mean of $6\frac{1}{2}°$ for the Arroyo Seco pebbles. Krumbein's sample 0–2 has been omitted from the San Gabriel data; it shows reverse imbrication, which Krumbein (1942, pp. 1386–1389) attributes to its position in the lee of a large boulder. If this sample is included, the mean inclination is only 4° upstream.

It might, perhaps, be better to project the long axes of pebbles into a vertical section parallel to the stream and to tabulate the dips of these projected lines rather than the true dips of the long axes. But the average inclination determined in this way would be less than 1°

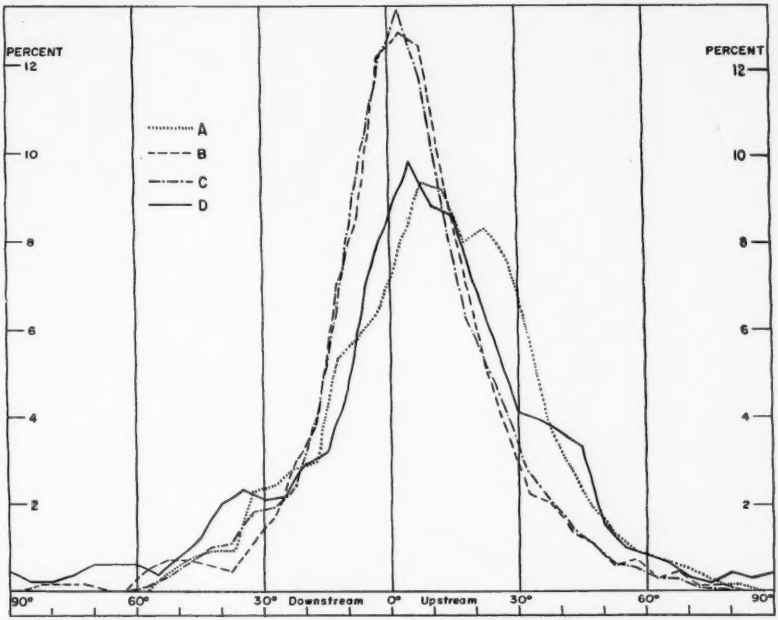

FIG. 4.—Frequency of pebble inclinations, San Gabriel Canyon and Arroyo Seco, California. Data expressed as moving averages of three 5° classes. Vertical scale gives percentage of total pebbles in each class. A. San Gabriel Canyon, true dip of long axes of pebbles with azimuths within 30° of stream course. B. Arroyo Seco, same. C. San Gabriel Canyon, apparent dip of all pebbles. D. Houghton conglomerate, apparent inclination of all pebbles with respect to bedding plane.

steeper than the average of the true dips, and the curves of figure 4 would be little changed.

Or secondly, Krumbein's data can be referred to a vertical longitudinal section of the stream on the basis of a very different assumption. If it is assumed that the mean attitude of the intermediate axes of pebbles will be more or less horizontal in a large sample, the probable attitude of the plane containing the long and intermediate axes of each pebble is established. This plane intersects the vertical section parallel to the stream, and the dip of the intersection can be determined from a table of apparent dips (e.g., Lahee, 1941, Appendix XIII, p. 804). The apparent dip of 500 pebbles from San Gabriel Canyon (sample 0–2 omitted, as above) computed on this basis is shown by Curve C, figure 4. As might be expected from the relation of apparent to true dips of planes in general, this curve is heavily weighted with low dips and is therefore more peaked than Curve A. The mean inclination is 5.5° upstream (4° if sample 0–2 is included).

The data from the Houghton conglomerate at the Allouez No. 3 shaft is shown by Curve D, figure 4. This has been recalculated for presentation on the same basis (percentage scale and 5° intercepts) as curves A, B, and C in figure 4, which accounts for the difference in appearance between this curve and the curve for all pebbles in figure 3.

As the actual direction of elongation of each pebble measured at the Allouez No. 3 shaft is not known, precise comparison with Krumbein's data is impossible. The methods of computing Curves A and C, respectively, give different weights to the principal variables—inclination, azimuth, and shape—that might affect a comparison with the data from the Houghton conglomerate. As both methods give similar if not identical results, and these results are similar to those obtained at the Allouez No. 3 shaft, the similarity in average inclination of pebbles in California and Michigan samples is regarded as significant.

In summary, the average inclination of 388 pebbles in the Houghton conglomerate shows a pronounced departure of about 8° from the dip of the bed itself. This departure is comparable to the departures noted in fluvial gravels from at least one modern locality and can be attributed to imbrication. It indicates that the stream or streams that deposited the conglomerate moved from southeast to northwest. Such data as have been presented on foreset bedding within the conglomerate bed also suggest the same direction of movement.

INITIAL DIP OF CONGLOMERATE BED

The initial dip of the conglomerate bed itself, as distinguished from the initial dip of individual layers within the bed, must have amounted to a good many feet per mile in order to provide a stream gradient. To the writer's knowledge, there is no basis, other than compraison of material with that of modern streams of known gradient, for determining what this initial dip might have been. The curves of figure 3, however, contain irregularities that might be more or less related to original horizontality. If similar irregularities could be found in curves for modern stream deposits of known gradient, and if a relationship to horizontality could be established, the phenomenon described below might provide a valuable tool for the investigation of ancient conglomerates.

If the curve representing the inclination of all pebbles in figure 3 is assumed to represent a normal curve of error, at least two possible computed curves might be fitted to it. The first would include all the data, would lie below the actual curve in the vicinity of 40° on each side of zero, and would be above it near 25° and 50°. That is to say, the empirical curve has pronounced "shoulders" at about 40° on each side, and the first curve would assume that these shoulders are irregularities due to the small size of the sample, and are not significant. As these shoulders are present in the curves for the much smaller samples representing individual size classes, however, these irregularities probably are significant, and the first curve would ignore important information. This curve, therefore, is not shown.

The second curve would hug closely the relatively straight flanks of the main peak, and lie below the actual curve where it has "shoulders." This second curve, constructed from ordinates given by Hodgman (1941, pp. 200–204), is shown as Curve A in figure 5. When points expressing frequency on this computed curve are subtracted from comparable points on the actual curve, an irregular curve (Curve B, fig. 5) with two peaks results. These two peaks also suggest curves of error, and Curves C1 and C2, figure 5, represent an attempt to fit the actual curves with computed curves in order to locate the probable means. Only minor changes can be made in the shape and position of these computed curves without spoiling the fit. It will be noted that these two computed curves of error are of almost the same dimensions and that their peaks fall at points that represent inclinations of 42° SE. and 36° NW., respectively, measured against the dip of the conglomerate bed.

A possible explanation of these secondary peaks is as follows: Where a pebble projecting above the stream bottom is appreciably larger than the material that underlies it, a small crater may form by scour in its lee. The pebble will slide or

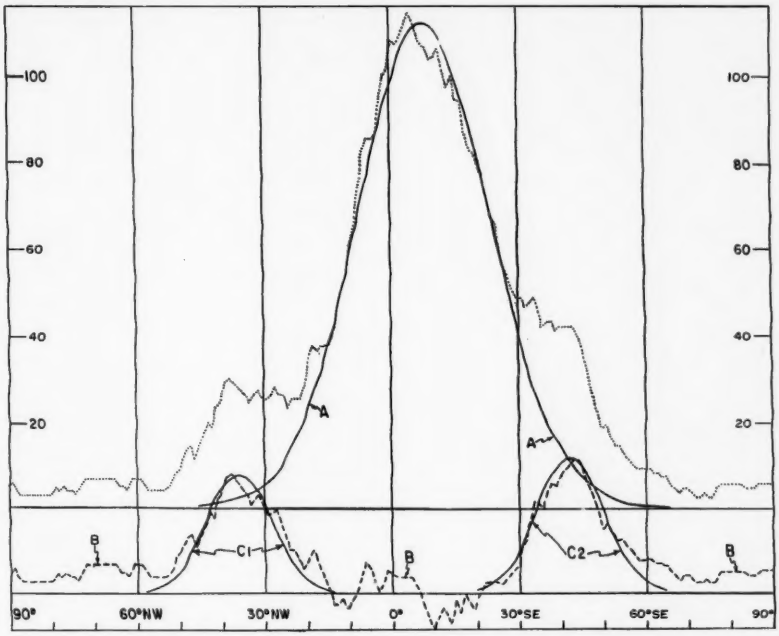

FIG. 5.—Analysis of frequency of pebble inclinations, Houghton conglomerate. Curve B is obtained by subtracting computed curve of error (A) from actual frequency curve (dotted line). Curves C1 and C2 are computed curves of error fitted to peaks in Curve B.

roll into a crater that becomes large enough to undermine it, and the pebble should then tend to lie with its long axis parallel to the near or far slope of the crater, depending on whether or not the current tips it over to the far side as it slumps into the crater. Smaller pebbles dislodged by formation of the crater may also slide in and acquire the same preferred orientation. As the slopes of the crater would be related to the angle of repose of the material in agitated water, they might tend to be the same on opposite sides of the crater with reference to a horizontal plane and to be relatively independent of initial dip of the stream bed as a whole. In the present example (fig. 6), the obtuse bisectrix of the two mean dips, a line inclined 87° NW. with respect to the conglomerate bed, might represent an original plumb line, and the initial dip of the bed as a whole would then be taken as 3° NW. The average inclination of the crater walls with respect to an original horizontal line would be 39°, and this would represent the angle of repose for the material and degree of agitation involved. Twenhofel (1950, p. 544) implies that 40° is about the maximum initial dip expectable in detrital material.

The tendency to form these two subordinate peaks is evident in the data for several of the individual size classes (figs. 2 and 3), even without subtracting a curve of error for the main peak. The three-peaked form is clearest and most symmetrical in the smallest-size group (less than 2 inches long), but well-developed shoulders are evident in the curve

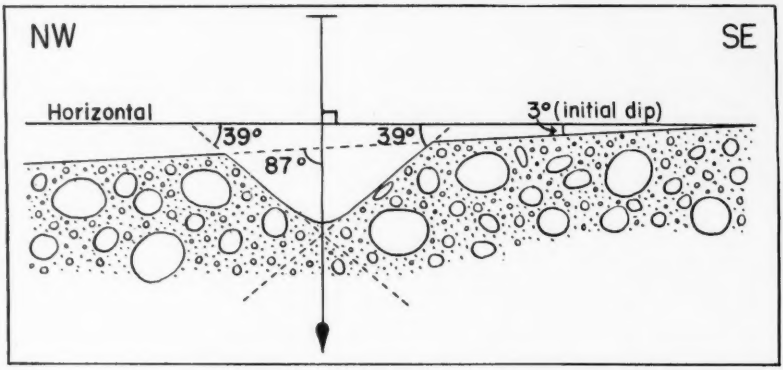

FIG. 6.—Cross section of theoretical scour crater. Obtuse bisectrix of angle between crater walls may have a fixed relationship to a horizontal line at the time of deposition, permitting determination of initial dip. Obtuse bisectrix assumed to be normal to original horizontal line in this diagram. Craters may be several inches in depth.

for the next larger size class. Pebbles greater than 8 inches long show a distinct secondary peak that reflects an upstream dip of about 40°. A similar peak would appear on the curve for pebbles 4 to 8 inches long had a smaller interval been used for the moving totals of figure 3 (see fig. 2). These differences in the curves for various size classes, if significant, might be explained as follows: Under conditions of deposition of the Houghton conglomerate, scour craters tended to form principally behind the larger cobbles and boulders, but a great many smaller pebbles, particularly those less than 2 inches long, tended to slide into the craters formed behind these larger stones. The smaller material was about equally dispersed on upstream and downstream sides of the craters, but when the larger cobbles and boulders were undermined and slid into a crater, they were generally tipped over by the current and now lie on the downstream side of the crater.

The limited amount of data available makes this analysis of initial dip in the Houghton conglomerate of little more than suggestive value unless the existence of a similar phenomenon can be established in modern fluvial sediments. Of the curves plotted in figure 4 from Krumbein's data, only Curve A has noticeable shoulders; these irregularities are not symmetrically disposed with respect to zero dip and are probably due to the small size of the sample (181 pebbles). Krumbein's pebbles were not selected for their elongation and are appreciably smaller, on the average, than those measured here. They were deposited in narrow canyons during a catastrophic flood. Conditions under which the Houghton conglomerate was deposited are not known, but they may have been quite different; the relatively even surface on which the bed was deposited was certainly very extensive laterally, and modern fan deposits or pediment gravels might provide closer analogies.

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FIGS. 1–4, DECEMBER, 1952

PRINCIPLES OF FACIES MAP INTERPRETATION[1]

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ABSTRACT

Facies maps based on numerical stratigraphic data (percentages, relative thicknesses, and ratios of lithologic components) are relatively new in the literature. Many such maps represent experiments in methodology, and the wide variety of patterns displayed on the maps presents many problems of interpretation.

In part, interpretation of facies maps depends upon the scale of the map, the magnitude of the stratigraphic interval, the geographic area involved, and the relative rate of change of the facies in the map area. In general, two types of maps are recognized: *regional maps*, which show broad trends over large areas, and *local maps*, which show greater detail in smaller areas. The distinction is partly on the basis of map scale, magnitude of stratigraphic unit, and density of control.

The isopach map of the stratigraphic unit is used as a base for the facies map, and interpretation of the facies patterns is closely related to interpretation of the isopach lines. The concept of "facies strike" and "isopach strike" are useful in map interpretation, inasmuch as they provide a basis for testing similarities or divergences between these two kinds of strike and the more familiar structural strike of the rocks.

The present paper reviews some of the principles of facies map construction and attempts to develop principles of map interpretation. These principles are based mainly on relations between the kinds of strike, on rates of change, and on an evaluation of the erosional modification of the original patterns.

INTRODUCTION

Facies studies have expanded rapidly within the past decade, largely because many new mapping methods were introduced. The facies concept itself is more than a century old, and in that time usage of the term has varied widely. Moore (1949) reviewed this usage, and suggested that the term be considered to "comprise any areally segregated part of a designated rock division in which physical-organic characters differ significantly from those of another part or parts."

The concept that facies is properly an expression of areal variation in rock aspect implies that an effective manner of showing facies is by maps. Facies maps probably were made as long as 50 years ago, but their modern development awaited the availability of subsurface data, permitting three-dimensional presentation of the stratigraphic unit.

An important concept related to facies is that of varying thickness of a stratigraphic unit. Isopach maps may be found in the literature as far back as the first World War, although the term isopach was introduced in the late 1920's, apparently by petroleum geologists. Facies maps drawn on isopach bases were prepared as oil company projects in the early 1930's, although their common appearance in the literature has been mainly since the early 1940's.

In part, modern facies maps awaited the introduction of numerical data into stratigraphy and sedimentation. The statement that a section consists of several hundred feet of sand and shale is too general for any but the roughest kind of facies map. More exact thicknesses of each rock type, and more detailed descriptions of the kinds of sand, shale, and limestone in the section permit increasingly sound types of maps to be developed.

There has been a fair amount of skepti-

[1] Expanded from a paper on "Research Trends in Sedimentology" presented before the Society of Economic Paleontologists and Mineralogists, 26th Annual Meeting, Los Angeles, March, 1952.

cism among geologists regarding the accuracy with which numerical stratigraphic data can be presented. In part, this arises from the common occurrence of covered intervals in outcrops, contamination of cuttings from wells, poorly expressed drillers' logs, and the like. However, modern subsurface techniques, including the advantages of recirculating for cuttings, diamond drill cores, electric and radioactive logs, and a host of other modern developments, permit expression of subsurface data with higher accuracy than can be had from the average outcrop.

This does not imply that early, more generalized data are not of value. Comparison of early well logs or nearby outcrops with recent logs shows that sufficient data for generalized isopach and lithofacies maps may be had from the earlier descriptions. There is an implied distinction here between maps used for detailed petroleum exploration and the more generalized maps used for reconstructing geologic history. For the latter purpose, the selected stratigraphic units commonly can be larger, more generally defined, and described more broadly than for exploration. An accuracy of the numerical data to within 5 or 10 per cent is adequate for many purposes.

Earlier facies maps involved regional studies of systems or series, usually with distinctions among sand, shale, limestone, and evaporites as sedimentary types. More detailed description of sediments (with distinctions among varieties of sands, limestones, etc.), combined with closer subsurface control and better correlation of thinner units permitted development of large scale local maps. With this development came new problems of expressing detailed facies; and differences in the scale of thinking showed the necessity for distinguishing between regional and local maps.

A regional facies map may be defined as one which shows the broad regional trends in lithology. Such a map may show that the stratigraphic unit is mainly shale in one area, becomes a mixture of shale and limestone in another, and finally culminates in a dominant limestone section. A local facies map may be defined as one which shows the detailed local variations in lithology, or shows local departures from regional trends. In an over-all section of sand and shale, there may be local sand shoe-strings which are "averaged out" in the regional map. Determination of the specific patterns of such sand bodies may be the objective of the local map.

As a general rule, regional maps involve the study of large time-rock or operational rock units over an appreciable area on a map of small to moderate scale (usually 1:1 million or less). The facies is expressed either in average or gross terms, or as specific lithologies. Control for regional maps is relatively open, i.e., the wells or measured sections are selected to give a relatively uniform but open spacing to the control points. On the other hand, local maps are usually prepared for thin stratigraphic units in small areas, on larger map scales (they may be as large as 1:10,000), using all available control.

It has been observed experimentally that if all available control is used for regional maps, the patterns may become greatly complicated by local variations. Experience tends to confirm the impression that it is preferable to sort out the local variations on special maps. A problem of major importance in facies mapping is the development of sound principles for selecting regional control points. Assuming that abundant control is present, how does one select a typical or average well or outcrop section? Where control is scarce, as in wildcat territory, how may one decide whether the section is regionally typical?

Assuming that such questions can be answered, and that reasonably accurate facies maps can be made, there still remains the problem of interpreting the patterns that are disclosed on facies maps. In some instances the patterns are simple subparallel bands which seem directly interpretable, whereas in others

a similar stratigraphic unit yields an extremely spotty map with little apparent rhyme or reason. One difficulty in proposing principles of facies map interpretation is that relatively few maps are available for detailed study. It is doubtful whether many geologists have seen as many as 100 facies maps. One need only compare this with the average geologist's experience with topographic and areal geology maps to see the limitations.

Despite present limitations in the development of sound principles of facies map interpretation, the writer feels that cumulative experience is great enough to demonstrate some of the variables which enter map interpretation. It is the purpose of this paper to describe some of the generalizations which seem to be supported by present knowledge.

FACIES MAPS

As stated earlier, facies maps show the areal variation in over-all aspect of stratigraphic units. The aspect represents the characteristics of the stratigraphic unit at any one control point, and facies is the expression of variation in characteristics laterally from the control point. Aspect may be expressed in terms of lithology, faunal content, tectonic implication, inferred environment of deposition, or in other ways. These give rise respectively to lithofacies maps, biofacies maps, tectofacies maps, and environmental pattern maps. The facies itself may be represented as the areal variation of a dominant aspect, an average aspect, or a specific aspect (Krumbein and Sloss, 1951, p. 403). The need for a variety of ways to express facies arises from the difficulty of finding any single feature of the rocks which completely describes their many characteristics.

Lithofacies maps are more common than other kinds, mainly because of the availability of lithologic data as compared with numerical faunal data. The principles of map construction are much the same, and in all likelihood principles of pattern interpretation may be similar. Most contemporary maps are based on numerical data, expressed as percentages or thicknesses of various lithologies, or as ratios of one lithologic type to another. The writer's greater familiarity with ratio maps accounts for their emphasis in this paper; percentage and other maps involve similar principles, some of which are described in detail by Low in LeRoy (1951).

Ratio maps are usually drawn on an isopach base, to provide a simultaneous picture of total present thickness and gross lithology. Reconstruction of former areal extent, original thicknesses, or inferred original lithology is kept to a minimum, so that the maps may be used as far as possible as a factual basis for preparation of paleogeographic and other interpretive maps.

The several ratios used are described in detail in Krumbein and Sloss (1951, chaps. 9 and 13). The ratio method is based on use of the end-member concept, which contrasts the relations among end members present. In essence the ratios yield easily visualized values which always state the number of feet of numerator-type rock per foot of demoninator-type rock. Thus, the clastic ratio (sand + shale)/(carbonate + evaporite) = 1.3 means that the section has 1.3 feet of sand and shale for every foot of limestone and evaporite. Similarly, in the same section the sand-shale ratio expresses the amount of sand per foot of shale, regardless of the amount of limestone or evaporite present.

The fact that all stratigraphic sections can be analyzed in terms of end members permits extensive use of 100-per cent triangle paper, on which any three end-member stratigraphic section can be plotted as a single point either by ratios or percentages (Krumbein, 1948). Even parts of sections, as for example the limestones, can be handled in the same way by letting the total limestone equal 100 per cent and forming ratios among two or more limestone types. In this manner the geometric properties of the facies lines remain the same regardless of the

end members used. This uniform geometric derivation of the lines thus becomes a constant factor in facies map interpretation.

The contour interval for ratio facies lines is commonly geometric rather than arithmetic, to bring out exponential facies trends, but this practice is not an essential part of the method. For certain rate of change studies an arithmetic interval is preferable. In any event, two sets of ratio lines are commonly shown on the same isopach base, which permits selection of limiting values for defining gross lithologic groups. Each of these may then be colored for easy visualization of the map patterns. It is recognized that the clastic ratio and sand-shale ratio yield non-specific lithofacies maps in which minor lithologies may be obscured. However, there is an almost infinite number of specific end member combinations which can bring out any desired type of lithology or lithologic characteristic.

PROBLEM OF SAMPLING THREE-DIMENSIONAL ROCK BODIES

The problem of spacing control points on a facies map is essentially statistical, inasmuch as it involves the question of adequate sampling of the stratigraphic unit. It has been pointed out by many writers that the volume of rock cut by a borehole is only an infinitesimal part of the total volume of the rock body penetrated. However, the sampling problem is not so much one of relative volumes as of obtaining representative sections. Assuming that complete sections (wells or outcrops) are available, the sampling problem may be approached in terms of four factors which involve the nature of the stratigraphic unit, the size and location of the geographic area, the uniformity of the stratigraphic unit, and the scale of map to be used.

The magnitude of the stratigraphic unit is important in terms of its gross thickness and composition. For large time-rock units, in which most facies techniques result in average values, the sampling problem may differ from that for thin units in which each lithology plays an important map role. The geographic area involved in the study (plus the thickness of the unit) largely determines whether the map is to be regional or local, and thus in part establishes the map scale. The uniformity or heterogeneity of the rock body influences the closeness of spacing. In many parts of the craton the rates of facies change are gradual, but as the margins of orthogeosynclinal belts are approached, they may be relatively rapid. Unequal spacing of control points, with greatest density in areas of rapid facies change, is usually indicated. The geographic location of the study area may limit the number of control points by lack of exploratory holes, absence of good exposures, or extensive erosion.

The writer is not aware that a rational theory of control point spacing has been developed. For the most part the practical problem is solved by rule-of-thumb methods. Where control is scarce, it is all used; where control is abundant, some choice may be made. The writer's experience with regional mapping has led him to favor relatively open control, to avoid the complexities brought in by local anomalies. Selection of the open control is influenced by several factors. One is that each control point should be "typical" of the section in that area. Subsurface workers or field workers with wide experience are usually able to decide quickly whether the section is regionally sound. Even in literature compilation, construction of rock correlation networks and cross-sections with all available data permits reasonable selection of map control. Lowman (1949) describes a method for setting up a correlation network.

Assuming that control is relatively abundant, the problem of control point spacing may be studied experimentally. Maps may be prepared of the same area and stratigraphic interval with increasingly tighter control, to observe the successive changes in the facies patterns. Such experiments commonly show that surprisingly open control affords maps

which are not much changed until the control becomes quite dense. For example, regional systemic studies on a 1:2.5 million base in the central states provide acceptable maps with only one control point per 2,000 square miles. This is about one well per two counties in midwestern states, and the control points are spread about 1.5 inches apart. The patterns do not significantly change until the control is tightened to the order of several wells per county, whereupon the broad facies trends begin to disintegrate into more patchy patterns. In short, it appears that local variations begin to dominate over the regional picture.

A second approach is to consider the increasing difficulty of writing numbers and drawing contours if the control points are very closely spaced on a map. Regardless of scale, spacings closer than about 0.5 inch become inconvenient, and optimum ease is achieved with spacings from 1 to 2 inches. When the points fall 4 or more inches apart, it becomes difficult to see the trends among the numbers.

This rather arbitrary rule provides one basis of selecting map scales in accordance with the detail desired in a study. On a 1:1 million base, one point per 8 townships (288 square miles) yields a base with points spread about an inch apart. On a scale of 8 inches to the mile, one well per 10 acres yields about the same spacing. The first density represents an optimum regional control and the second represents an extremely detailed study.

Figure 1 shows three base maps on a 1:1 million scale, with three densities of control points. The control point density increases by a factor of 4 in successive maps, with average spacings of 1.5, 0.75, and 0.375 inches. In the writer's opinion, the optimum density for most regional maps lies somewhere between maps A and B. Map C obviously has too small a spacing for convenience. With this tight control the map scale should be increased. In this connection, individual control points may be field wells, and it is sometimes advantageous to average several field wells to obtain a characteristic regional value, which may be plotted at the center of the spread.

The interpretation of regional maps is influenced by the spacing of the control points, and in this paper it is assumed that the spacing lies between 1 and 2 inches, which is perhaps slightly more open than the optimum density.

ISOPACHS AND FACIES LINES

One of the conspicuous features of facies maps is the relation between isopachs and facies contours. In some maps the sets of lines trend in the same directions, and in others the relations between the two kinds of lines may be complex. The concept of "isopach strike" and "facies strike" are useful in evaluating these relations. Isopach strike may be defined as the compass direction of the isopach lines. An isopach map is a two-dimensional projection of a three-dimensional solid with assumed horizontal flat top, and the isopach lines represent traces of horizontal planes along the edges of the solid. On the other hand, facies lines represent traces of vertical surfaces which cut the solid into blocks. Hence, facies strike may also be defined as the compass direction of the facies contours.

Many facies maps consist of two sets of facies contours superimposed on the isopach base. In some instances one set of facies may have the same strike as the isopachs and the other may transect them at some angle. In general, there seem to be at least six relations which can be discerned between any set of facies lines and the isopachs. These are illustrated in figure 2, where the solid lines represent isopachs and the dotted lines may be taken as clastic ratio lines, sand-shale ratio lines, or some other lithologic representation. The six examples are not presented as a formal classification, but rather as suggestions for further study. The distinction between the linear and ovate patterns is partly one of map scale, but the intention is to suggest degrees of similarity or difference in typical situations.

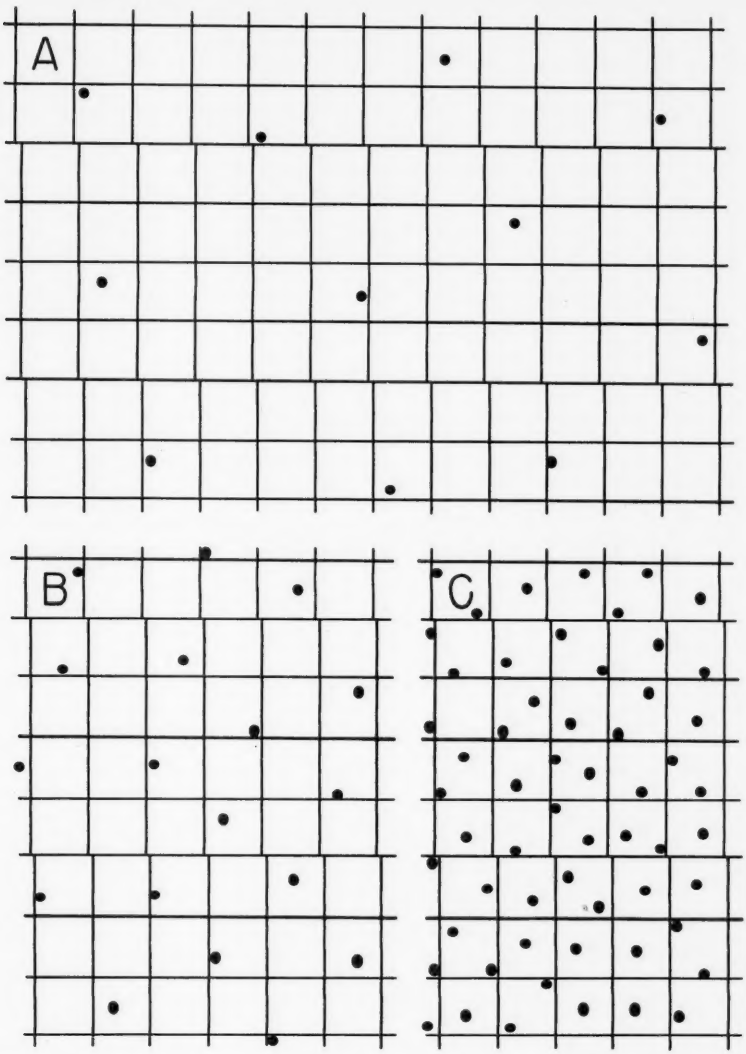

FIG. 1.—Portion of 1:1 million base map, showing three densities of control spacing. A—one well per 9 townships; B—one well per 3 townships; C—one well per 0.7 townships.

Examples can be cited for each of the classes shown in figure 2. As typical illustrations, the linear subparallel pattern may occur under conditions where

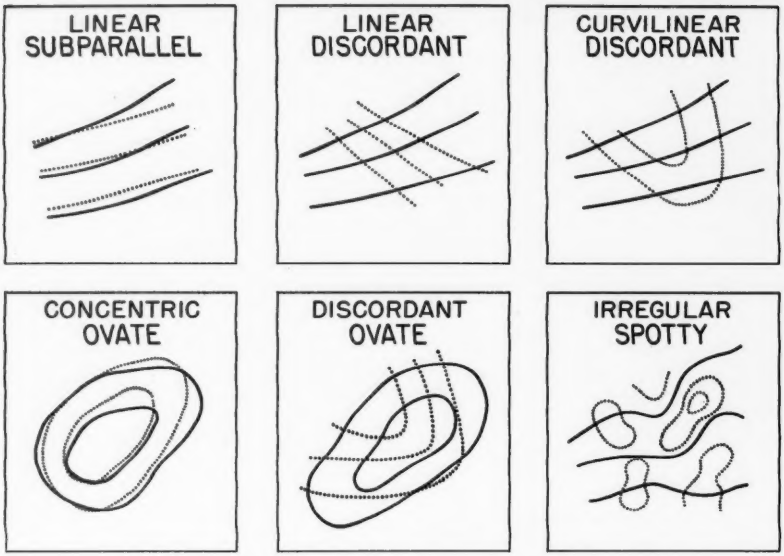

FIG. 2.—Simplified diagram of relations between isopachs (solid) and facies lines, showing six common classes.

clastic sediments are spread over a subsiding area in decreasing amount away from the source, so that the clastic ratio lines tend to decrease as the isopachs increase because of increasing lime deposition. The curvilinear discordant pattern may arise when a local concentration of clastics is poured into a subsiding area, as in a delta. Here the clastic ratio lines may project farther into the basin than normally. The concentric ovate pattern is characteristic of evaporites in an intracratonic basin. The irregular spotty pattern occurs near the deteriorating edges of sheet sands, where the accumulation becomes patchy or spotty.

When two sets of ratio lines accompany the isopachs, the relations become even more complex. The clastic ratio lines may parallel the isopachs and the sand-shale ratio lines may be curvilinear discordant; or one ratio may yield a simple pattern and the other be irregular spotty. Commonly, interpretation is facilitated by drawing individual ratio maps, and studying the relations between 1) clastic ratio and isopachs, 2) sand-shale ratio and isopachs, and 3) clastic ratio and sand-shale ratio. By sorting out the individual effects and checking them back to the original logs or measured sections, it is usually possible to infer the combination of conditions which produced the observed effect. Because of the similar geometric derivation of all lithologic ratios as mentioned earlier, the same reasoning applies to facies maps based on any selection of end members.

When color patterns are superimposed on the map in terms of limiting values of two lithologic ratios, the relation of the color patterns to the isopachs represents a kind of average relation between facies patterns and thickness. Two rather common situations occur, as shown in figure 3. In one, the ruled patterns are aligned with the isopachs, indicating fairly close relation between lithologic response and

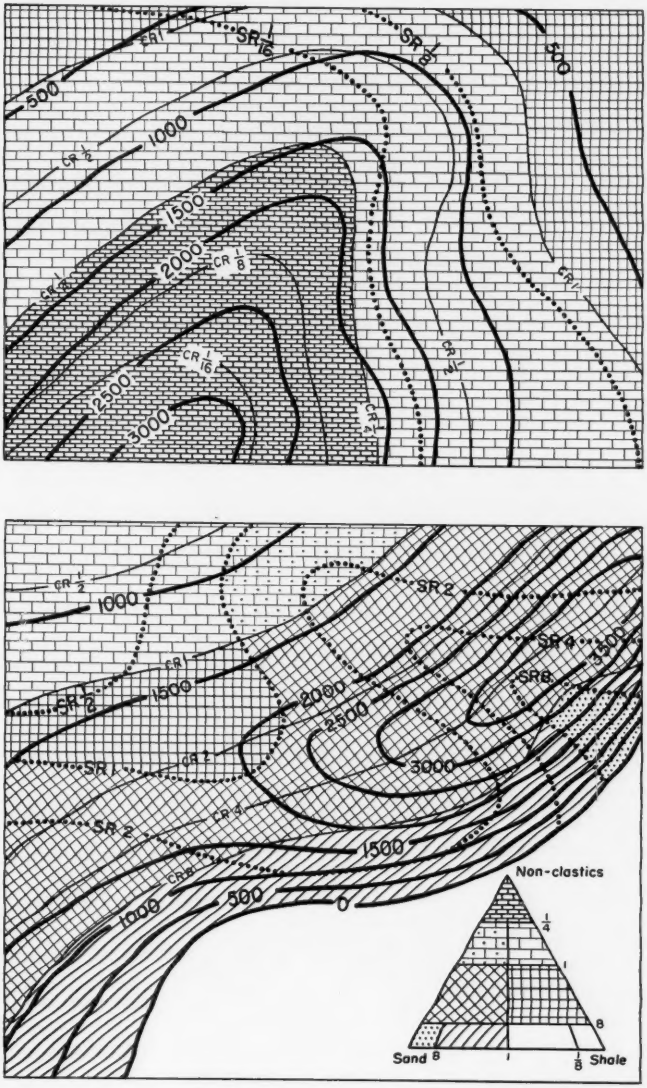

FIG. 3.—Portions of two hypothetical facies maps showing parallelism and discordance among isopachs and facies lines and patterns. The legend triangle applies to both maps.

subsidence; and in the other the ratio lines and ruled patterns weave across the isopachs, sometimes because the two ratio lines are locally strongly discordant. These latter patterns are often among the most difficult to interpret, but they suggest that while one ratio responds to general tectonic conditions, the other ratio line may respond to local sources, currents, or other conditions.

Post-depositional erosion greatly disturbs the relations among facies and isopachs. In the preceding discussion, it is assumed that the stratigraphic unit has a conformable top; where this condition does not hold, as along the edges of many maps, the discordances in the patterns may be wholly erosional. It is not safe to assume, however, that where the patterns are irregular there must have been some erosion. Several criteria for helping to distinguish between erosional and depositional zero isopach lines are given in Krumbein and Sloss (1951, p. 445). With some modification, these same criteria may be applied to analysis of the central portions of facies maps.

TECTONIC AND ENVIRONMENTAL INTERPRETATION OF FACIES MAPS

Facies maps are made for several purposes, including reconstruction of geologic history, interpretation of environmental conditions, evaluation of the contemporary tectonic framework, and for a variety of economic uses. Regional facies maps of thick time-rock units have most value in the first three instances; detailed exploration maps usually involve thinner units and larger scales. However, even the broader maps have industrial application in setting a framework for more detailed studies.

Regional maps of the kind considered here provide data on three important questions. They show 1) the present areal distribution of the stratigraphic unit, 2) the present variation in thickness of the unit, and 3) the over-all or gross lithology of the unit. Such maps commonly afford a basis for evaluating the broad controlling conditions of sedimentation in terms of the tectonic framework, the distribution of source areas, and in some instances the sedimentary environments which prevailed. Some of these features can be discerned in part from the relations between isopach and facies lines.

Figure 4 is a chart which attempts to show the response of map patterns to the tectonic framework and source areas. The upper portion shows shelf and intracratonic basin conditions with three postulated types of source area. The central portion of the figure lists the six isopach-lithofacies combinations of figure 2. The lines connecting the blocks suggest several combinations of conditions which may produce the map patterns. The relations are probably more complex than shown, but the chart suggests on the basis of present knowledge that certain combinations of tectonism and source tend to produce characteristic map patterns.

The generalizations suggested by the upper half of figure 4 are that shelf deposition tends to produce linear or spotty patterns, and that intracratonic conditions tend to produce ovate patterns. In addition, the specific patterns within each framework are partly influenced by the nature and location of the source area. It is recognized that shelves and basins may be of variable size, so that the chart refers mainly to rather broad features on the craton. Patterns in linear geosynclinal belts have not been studied extensively, but they also appear to include both simple linear and complex discordant elements.

It is to be recalled that in all regional maps of thick stratigraphic units, there may be a serious averaging process which of itself often introduces lack of pattern coincidence. Two radically different sections, one with interbedded clastics and non-clastics throughout, and the other with basal clastics and higher non-clastics may show up in the same color pattern. In some instances, such relations suggest that the interval be divided into two or more thinner parts for separate mapping. In other instances, proper selec-

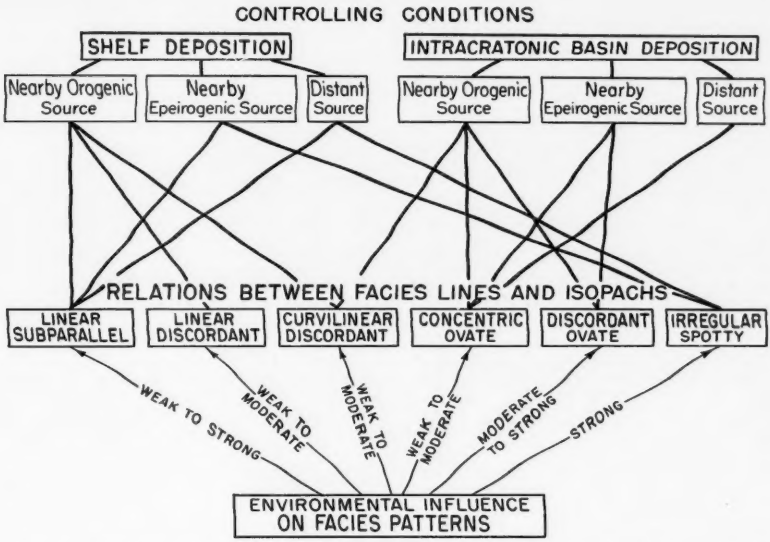

FIG. 4.—Relations between facies lines and isopachs in terms of tectonics and source areas. Lower part of diagram suggests nature of environmental influence on patterns.

tion of end members or use of vertical variability maps may eliminate the difficulty.

Environmental interpretation from conventional facies maps usually is not satisfactory, although certain lithologic associations suggest the nature of the environment. For example, a high evaporite-carbonate ratio within a concentric ovate isopach-facies pattern implies a specific restricted environment. The lower part of figure 4 suggests the degree to which the sedimentary environment may influence or control the patterns within the prevailing combination of tectonic and source conditions. As the arrows indicate, these influences may be weak to strong, with the clearest relations commonly discerned in shelf conditions or in special restricted intracratonic basin conditions.

More detailed information on environments can be obtained from regional maps which contrast certain lithologic assemblages. In earlier publications (Krumbein, 1948; Krumbein and Sloss, 1951, p. 276) several end-member combinations useful in environmental interpretation are suggested. By forming a shale triangle with characteristic end members, it is sometimes possible to discern ancient shore trends from the relations among the ratio lines. Similarly, ratio analysis of non-clastics may shed light on open circulation and restricted environmental conditions.

As long as the special facies maps for environmental interpretation are based on ratio combinations, the same geometric patterns as shown in figure 2 may be seen. The geologic interpretation is somewhat different, but the principle appears to hold that coincidence among the facies and isopach lines suggests broad environmental controls on sedimentation, whereas transecting patterns suggest special influences, such as environmental barriers and other features which may keep one ratio response relatively uniform and permit variation in another. The same

averaging effect mentioned for conventional maps applies to environmental analyses, and judgment is required in selecting mapping units and end members.

INTERPRETATION OF ISOPACH AND FACIES RATES OF CHANGE

The relative spacing of isopach and facies lines indicates the rapidity with which thickness and facies change across the map. Isopach contours usually follow an arithmetic interval, and the rate of thickness change is inversely proportional to the spacing between the isopach lines. When facies lines are contoured on a geometric interval, a similar relation holds, but the rate of change is a function both of the spacing and the contour values. Experimental slope maps have been prepared, which show by contours the rate at which thickness or lithology varies. These are not entirely satisfactory as far as the writer's experience goes, but several interesting implications arise from them.

One problem commonly encountered in facies map interpretation is selection of the boundary between shelf and intracratonic basin areas. In many instances the isopachs and facies do not change concurrently, and the question is whether to use facies change or thickness change as an index of tectonism. There are some grounds for using thickness as a measure of subsidence, in which case one may discern a facies lag or facies projection beyond the selected boundary. In part, such relations may suggest that basin sediments "spilled over" onto the shelf, or that shelf sediments were washed into the subsiding area.

There is a large field for analysis in the study of facies and thickness rates of change. Such studies are more illuminating with relatively thin conformable intervals, although many broad regional maps are amenable to this analysis.

In comparing regional and local facies maps, the rates of change commonly indicate the extent and degree of local facies anomalies. Such comparisons may be of significance in economic studies, especially along the edges of sheet sands, near boundaries of tectonic elements, and in transitional environmental zones. In detailed academic studies, the local anomalies may shed light on local source areas, on varying effects of erosion, and on minor configurations of shore lines.

FACIES AND STRUCTURE

Isopach and facies maps are projections of three-dimensional rock bodies which are assumed to have a horizontal top. In nature the rock bodies are bounded by surfaces which may be folded or otherwise disturbed. A structure contour map prepared on the top of the stratigraphic unit used for facies analysis shows the actual configuration of the upper surface. One of the features involved in complete facies map analysis is the relation between facies and structure. The economic value of such relations is obvious; the more academic aspects also deserve some comment.

In general, three relations among isopach strike, facies strike, and structural strike may be discerned. These are summarized in the following table:

TABLE 1.—*Relations among isopach, facies, and structural "strikes"*

1. All three are parallel
2. Two parallel, one discordant
   a. Facies and isopach parallel, structure discordant
   b. Isopach and structure parallel, facies discordant
   c. Facies and structure parallel, isopach discordant
3. All three are discordant

Each of these classes carries interesting implications, and when more than a single facies ratio is plotted on the map, the relations may become even more complex because of lack of coincidence among the facies ratio lines themselves. In this discussion, only the simpler case is considered, which may be taken to include facies patterns rather than the individual facies lines.

When all three elements are parallel, the implication is that the isopachs and facies responded simultaneously to con-

temporaneous subsidence, and that no serious structural disturbances occurred since deposition. This condition is suggested by some stratigraphic intervals in the Michigan Basin, which at most suffered some additional subsidence since their deposition.

When all three features are discordant, the implication is that later structural deformation cut across the original trends of subsidence, which themselves did not accord with the original facies trends. Some stratigraphic intervals in the Salina-Forest City Basins, disturbed by the Nemaha uplift, suggest these relations.

The class with two elements parallel and one discordant is perhaps the most interesting academically. Where facies and isopach are parallel and structure discordant, the relations imply an initial concurrent response of isopachs and facies to subsidence, with subsequent structural disturbance. Instances of this relation are fairly common, and may be seen in the Pennsylvanian of southeastern Colorado, where the Las Animas uplift (Cretaceous) cuts across isopachs and facies related to the Apishapa uplift (Pennsylvanian).

Where isopachs and structure are parallel, with facies discordant, the implication is that the isopach-facies discordance was contemporaneous with deposition, and that the isopach-structure parallelism indicates no serious structural changes since deposition.

The special case of facies and structure parallel with isopachs discordant suggests coincidental relations in some instances. In others, there may be a suggestion of initial isopach-facies discordance, as may occur where bioherms abut against thick shale accumulations; in subsequent deformation the more rigid bioherms may influence structural response.

All the cases cited assume no erosion since deposition. Where erosion has occurred, the relations may fall into any class. Moreover, the emphasis in the discussion is on regional structural trends; local structural features may show continuous growth through time, or secondary structures may develop on regional trends, giving rise to very complex local relations.

CONCLUDING REMARKS

Increasing interest in facies maps academically and in industry has brought out the need for systematic principles of facies map interpretation. Because of the relatively few modern facies maps in the literature, it is not possible at this stage to compile a comprehensive collection as was done with topographic maps by Salisbury and Atwood (1908). Nevertheless, cumulative experience, though limited, permits some discussion of facies map interpretation. Undoubtedly, the principles will be sharpened as experience grows, and it is the writer's hope that the present paper may stimulate further thought on the subject.

The writer is indebted to his colleagues at Northwestern University, his former students, and to many individuals in a number of oil companies for helpful suggestions in formulating his thoughts on the subject. Research grants from the Graduate School at Northwestern University furnished support for a number of experimental map studies.

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FIGS. 1–9, DECEMBER, 1952

THE ORIGIN OF STYLOLITES[1]

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ABSTRACT

The origin of stylolites is not clear. The writer's field observations in Southwestern Germany showed that the stylolites there most probably were formed by solution of precipitated calcareous mud during sedimentation.

INTRODUCTION

Recent discussions in the American literature[2] show that the problem of the origin of stylolites still exists. The following paper which is the result of field observations in Germany in 1946–49 presents a new approach to the solution of this problem. The writer realizes that his ideas may not be accepted readily, but other hypotheses on the origin of these particular stylolites are less satisfactory. This does not mean that "pressure-solution" and other types of stylolites do not exist, for it is probable that stylolites originated in several different ways.

The subject of the origin of stylolites has been studied for a long time. However, most of the ideas proposed, excepting the contraction-pressure and the pressure-solution hypotheses, have historical importance only and are not discussed in this paper.[3] The contraction-pressure hypothesis was proposed by Marsh (1867), Gümbel (1882, 1888), and others. The latest modification of these ideas is that of Shaub (1939, 1947, 1949), and according to him the stylolites were developed in unconsolidated sediments as "plastic flows" under the load of the overlying ooze. Thin clay layers in the calcareous ooze were considered very important in this process. According to the pressure-solution hypothesis (Wagner 1913, Stockdale 1922–1945, and others) which is still the most widely accepted explanation of stylolite formation, this type of structure was formed in solid rocks by solution favored by pressure. The pressure could have been due to the load of overlying strata or to tectonic forces. The presence of stylolites was thought to indicate differential solution which may be caused by a non-uniform pressure or by unequal solubility of rocks.

OBSERVATIONS

In order to test these hypotheses the writer studied about 75 outcrops of the Muschelkalk, which is well known for its stylolites (Wagner 1913, Stockdale 1922), and some 20 outcrops of the Malm limestone in the provinces of Wuerttemberg and Baden in Germany. The location and the relationships of the outcrops are shown in figures 1 and 2. The geology of the area has been described in "Erläuterungen zur geologischen Spezialkarte von Wuerttemberg."

The Muschelkalk.—The Middle Triassic Muschelkalk series is subdivided into 3 groups: a) Lower Muschelkalk about 50 m. thick; composed of limestone, dolomitie, and marl; b) Middle Muschelkalk 20–80 m. thick; composed of dolomitc limestone, dolomite, marl, anhydrite, gypsum, and rock salt; c) Upper Muschelkalk about 65m. thick; composed of 1) Trochitenkalk (25 m.)

[1] The writer is indebted to Dr. J. W. Gruner, Dr. G. A. Thiel, and Mr. J. A. Fraser for a discussion of the problem and for a reading of the manuscript.

[2] Shaub 1939, 1947, 1949; Stockdale 1939, 1943, 1945; Bastin 1940; Goldman 1940; Conybeare 1950; Twenhofel 1950.

[3] For the history of the problem and a good description of stylolites see Stockdale, 1922.

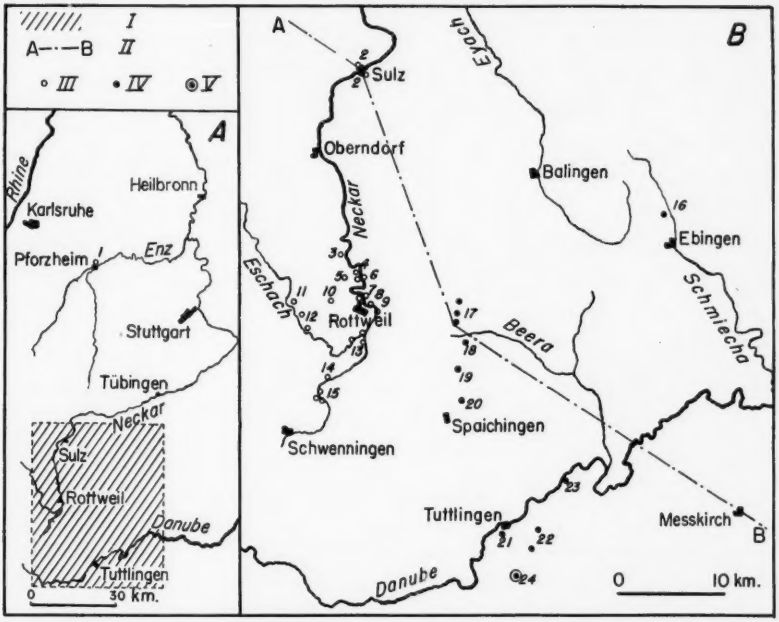

FIG. 1.—Location of the most important outcrops studied by the writer. Legend: I, Sulz-Tuttlingen area shown on general map of Southwest Germany; II, Location of the cross section shown on fig. 2; III, Outcrops of the Muschelkalk; IV, Outcrops of the Malm limestone; V, Outcrop of the Nagelfluh; A, General map of a part of Southwest Germany showing the outcrop in Pforzheim and the Sulz-Tuttlingen area; B, The Sulz-Tuttlingen area.

Muschelkalk outcrops.—1, Old pit in Pforzheim near the Romanic Tower; 2, Several outcrops in Sulz on both banks of the Neckar River; 3, Several outcrops on the Talhausen-Villingendorf highway; 4, Several outcrops at the Neckarburg (the strata are strongly folded and brecciated in some places); 5, Small outcrops on the slope of the dry valley of the old Neckar at the Neckarburg; 6, Several outcrops on both banks of the Neckar River near Tierstein; 7, Several outcrops on both banks of the Neckar River near the "Pulver Fabrik"; 8, Several outcrops on the Rottweil-Balingen highway; 9, Several outcrops between the electrostation and Gölsdorf on the east bank of the Neckar; 10, Some outcrops in and near Zimmern; 11, Several old pits near Flözlingen on the east bank of the Eschach; 12, Several pits and outcrops between Flözlingen and Horgen; 13, Several outcrops on both banks of the Eschach in Bühlingen; 14, The large pit west of Deisslingen on the right bank of the Neckar; 15, Several old pits and outcrops near the water mill west of Deisslingen on both banks of the Neckar.

Malm outcrops.—16, Small pit near Truchtelfingen; 17, Several outcrops on the Swabian Jura ridge on Oberhohenberg, Hohenberg, Lemberg; 18, Pit near Gosheim; 19, Large bluff at Klippeneck; 20, Several outcrops on the Dreifaltigkeitsberg; 21, Outcrop near the Tuttlingen railroad station; 22, Several outcrops southeast of Tuttlingen; 23, Several outcrops near Mühlheim.

Nagelfluh outcrop.—24, Windegg.

more or less thickly bedded gray limestones, dolomitic limestone, and dolomites. Bedding planes are covered by a thin film of a black clay; the rock in some places is rich in crinoids and mussel fragments; 2) Nodosusschichten (20 m.) thin bedded limestone; 3) Trigonodusdolomit (20 m.) thickly bedded dolomitic limestone and dolomite which form the top.

In the Rottweil area the stylolites in

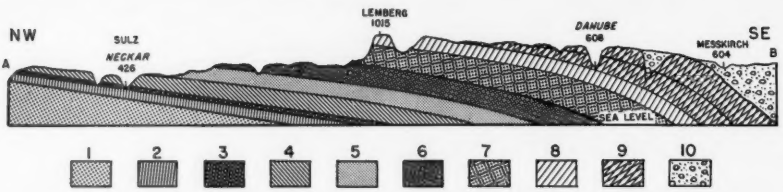

FIG. 2.—Schematic cross section through the Swabian Jura (=Alb). Vertical scale exaggerated 9 times; elevations shown in meters above sea level. Legend: 1, Bundsandstein—Lower Triassic; 2, Lower Muschelkalk—3, Middle Muschelkalk—4, Upper Muschelkalk—Middle Triassic; 5, Keuper—Upper Triassic; 6, Lias—Lower Jurassic; 7, Dogger—Middle Jurassic; 8, Malm α, β—9, Malm α, δ, ϵ, ξ —Upper Jurassic; 10, Tertiary. Modified after Bräuhäuser, 1938.

the Muschelkalk occur only at certain levels in Trochitenkalk and were seldom found in the overlying and underlying horizons. However, they are known in the uppermost part of the Middle Muschelkalk in the neighboring regions. The largest seams are found near the bottom of the Trochitenkalk, but some smaller seams do occur also in its upper part. The stylolites are absent in rocks showing wide variation in solubility and in the cavernous "Zellenkalk" in the Middle Muschelkalk and Keuper.

The above type of seam occurrence was also observed in the Neckar valley west of Deisslingen, where the river cuts an area of comparatively recent tectonic uplift, and also near Talhausen and Sulz, where the river cuts faults, and again at Neckarburg where the strata have been highly folded and partially brecciated. In each of these areas the stylolites do not show any relation to the tectonic pattern.

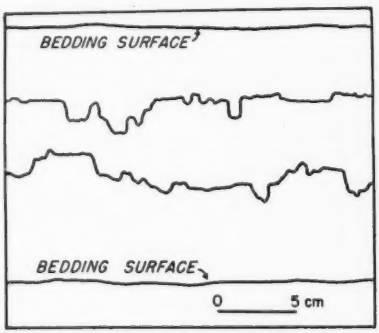

FIG. 3.—Two stylolitic seams located in the same bed. The columns in the seams bear no relation to neighboring seams. Muschelkalk; large pit west of Deisslingen.

The stylolites occur always in the form of seams parallel to the bedding. They are found only in the thicker beds (20–40 cm.) and the distances between seams range from 2–3 cm. to 3–4 m. The beds with seams are interbedded with the seamless beds but in some places there are 2 to 3 seams in one bed. The location of the columns in a seam is independent of those in neighboring seams even in the same bed. That is to say, the columns in one of the seams may be located over depressions, columns, or flat parts of the other seam (fig. 3).

The largest stylolites occur in the largest seams and are scattered over the widest areas. The small seams contain small columns that are exceedingly variable. Some seams branch into several seams and others penetrate each other and some even penetrate bedding surfaces (fig. 4).

The height of the columns ranges from 1–2 mm. to more than 7 cm. The large well-formed stylolites have striated side surfaces and in some places the striations are curved (fig. 5). Several columns become narrower at the bottom. Oblique sections of normal columns give similar pseudo forms. The foregoing refers, however, to the true forms. Some fossils were

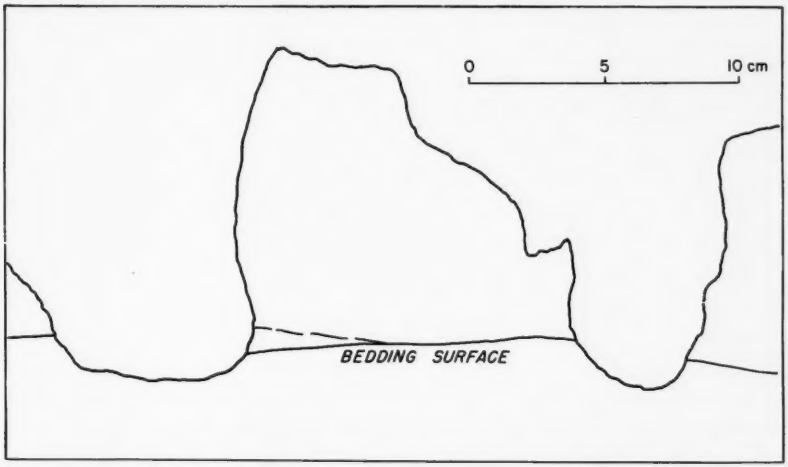

FIG. 4.—A large stylolitic seam cutting a bedding plane; walls of the stylolites are somewhat concave. Muschelkalk; Pforzheim.

observed on the tops of columns but such occurrences are rare. More often the stylolites cut fossils. Near Deisslingen large fucoids were found on the surface of one stylolitic seam. All surfaces of the seams are covered by a thin, fatty, black skin that is rich in colloidal matter and similar to the films on bedding surfaces. Undulation seams (fig. 6) were found together with typical normal seams and

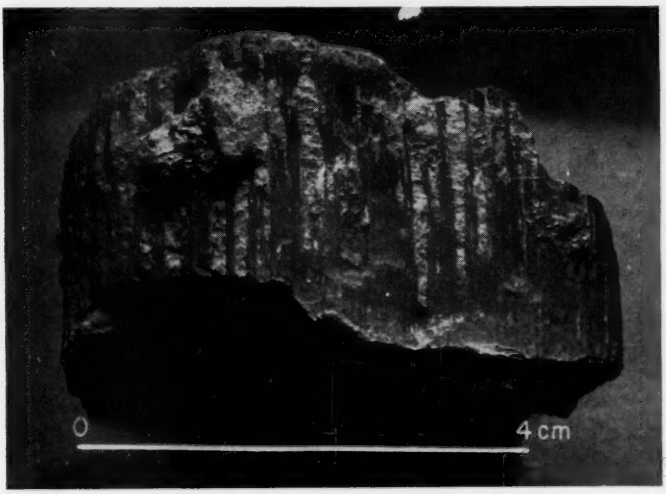

FIG. 5.—Curved striae on side surfaces of stylolite. Note: The neighboring striae are normally straight. Muschelkalk; large pit west of Deisslingen. Photo L. W. Weis.

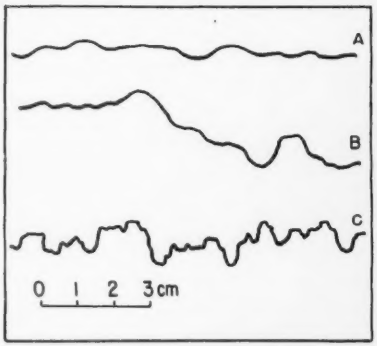

FIG. 6.—Three kinds of stylolitic structures in Muschelkalk: A, Undulation seam; B, "Half undulation-half stylolitic" seam; C, Typical stylolitic seam. Muschelkalk; large pit west of Deisslingen.

in some places they grade laterally into each other.

The Malm limestone.—The Upper Jurassic (Malm) in Wuerttemberg is subdivided into 6 zones; Malm α, β, γ, δ, ϵ and ξ which formed the top. It is represented by bedded facies (limestone and marl) and reef facies (massive limestone and dolomite). The writer studied only the bedded facies of the Malm β limestone. The rocks are represented by white, pure limestone beds 20–50 cm. thick, interbedded with gray marl layers 1–7 cm. thick. The strata are more or less horizontal.

The stylolitic seams occur independent of the tectonic framework and they are more numerous on ridges of the Swabian Jura (Driefaltigkeitsberg) than along the Danube (Meulheim-Tuttlingen) where the Malm plunges steeply in the direction of the Alps (fig. 2). The number of seams in the outcrop in Tuttlingen is smaller close to the fault which cuts the outcrop.

Only vertical or near-vertical seams were found in the Malm limestone (figs. 7,8). Most of the columns show complicated sharp-pointed end- and side-surfaces. The seams generally cut one or, at places, two or three beds. In crossing the bedding planes small offsets were occasionally observed. In a plan view the seams are not always parallel. The smallest horizontal distance between the seams is 10–20 cm., but usually it is 1–3 m. Near Gosheim the columns in one seam are not parallel to the micro-bedding. Many curved columns were found (figs. 7b, 8) but undulation seams are absent. Near Truchtelfingen the writer found a belemnite which penetrated a seam.

FIG. 7 (a).—Vertical seam from Malm β limestone. Klippeneck. Photo L. W. Weis.

According to geological maps (Map No. 152 and others), stylolites also occur in the overlying layers of Malm, where they are represented by normal horizontal seams.

EXAMINATION OF EXISTING HYPOTHESES

The origin of the structures described above cannot be explained by the pressure-solution hypothesis (e.g. Shaub 1939–1949):

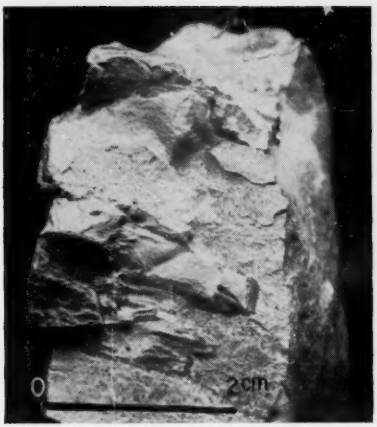

FIG. 7 (b).—Vertical seam from Malm β limestone. Columns are not parallel and some are curved. Tuttlingen, near the railroad station. Photo L. W. Weis.

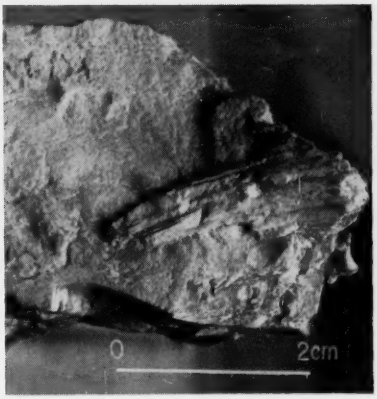

FIG. 8.—Curved stylolite from Malm β limestone. Stylolites on the opposite side of the same specimen and the neighboring columns are straight. Dreitfaltigkeitberg. Photo L. W. Weis.

I. The static and dynamic pressures on small surfaces in rocks are more or less uniform and cannot cause differential solution. Stockdale (1922, p. 49) and Twenhofel (1932, p. 738; 1950, p. 613) discussed the "concentration of pressure" along column axis and this could account for the development of the seams in the pitted pebbles described by Bastin (1940).[4] However, the location of the columns in the neighboring seams in the stylolites described by the writer is quite irregular. This distribution does not suggest pressure concentration action. Moreover, the stylolites were not observed in the cavernous limestones, where the "concentration of pressure" would be the greatest.

II. Stylolite-bearing horizons do not coincide with the lowest horizons of the strata where the load-pressure is at a maximum. Thus the origin of vertical seams in the Malm could not be caused by the vertical load-pressure, and furthermore, the relationship to tectonic forces is absent. It is difficult to explain how the same action could develop the vertical seams in Malm β and the horizontal seams in the overlying part of the Malm and also in the underlying Muschelkalk.

Wagner (1913) wrote about the influence of tectonic pressure on stylolitic growth, but this relationship was not observed in any of the outcrops studied by the present writer.

III. Stylolites occur in compact carbonate rocks where the circulation of groundwater is restricted and the amount of water is small. More favorable conditions for solution are present along bedding planes, but stylolite seams occur in general within the beds, not between beds. No relationship between seams and groundwater levels was apparent.

IV. Pressure-solution action would cause a removal of material and reduction in thickness (40% or more, Stockdale 1926). However, seams occur only

[4] These, especially the famous Tertiary "Nagelfluh," were often used as a proof for the pressure-solution hypothesis. For an examination of the universality of such a proof the writer studied a Nagelfluh in Windegg (fig. 1). Here as in other locations of pitted pebbles there was extreme concentration of pressure on small surfaces of contact between pebbles. However, solution did not form stylolitic seams, but only small round holes with rather smooth surfaces.

in thicker beds which do not change their thickness in stylolite-bearing and stylolite-free parts, regardless of the size of the columns.

Pressure-solution agents are universal, so that stylolites would be expected to occur in all limestones, especially in older and metamorphosed rocks, where pressure and solution effects reached their maximum. However, there are several old limestones which do not show these structures and Stockdale (1922, p. 13) pointed out their absence in metamorphosed rocks. Later (1939, 1943) he wrote about the seams in marbles, in all probability referring to the "Tennessee marble," which is not a true high-grade metamorphosed rock (Shaub 1949).

V. Sedimentary rocks are most isotropic in the direction of bedding and most anisotropic in the direction normal to the bedding, so that stylolites which, according to the pressure-solution hypothesis, indicate the most resistant parts of the rock should be located along the bedding. However, they are usually located prependicular to the bedding. Moreover, columns often cut units with quite different solubility, with fossils, with other seams, and even bedding planes. According to Stockdale (1922) undulation seams were formed by continued solution of rocks. However, they grade into normal seams over short distances in which the composition and solubility of rocks do not show any marked changes. Although, according to Stockdale (1922, pp. 50, 53), the side surfaces of columns would have been unattacked by solution, they always show a residual clay covering.

VI. The several characteristics of stylolites could be developed more easily in soft sediments than in solid rocks. In this category belong columns which are curved or corroded, and narrowed at the bottom. To explain their origin by partial resistance of solid rock is often impossible. To account for the origin of striations on side surfaces of columns is a difficult problem using the pressure-solution hypothesis (Stockdale 1922, p. 64). The development of a partially curved striation in solid rock is impossible.

VII. The occurrence of fucoids on seam surfaces as well as on bedding surfaces show that these surfaces were ordinarily sea-bottom surfaces.

An alternative hypothesis, that of contraction-pressure is likewise unsatisfactory in an attempt to explain the origin of the stylolites that have been studied (e.g. Stockdale 1922–1943 and others):

1. Many features, especially the kind of stylolitic clay films, suggest the solution origin of stylolites. The contraction-pressure idea fails to explain the origin of clay layers belonging to vertical seams. Gümbel's (1888) "movement of marl fragments into the mud" is improbable in horizontal strata.

2. It does not explain why only a small clay layer *in* the beds contributed to the development of stylolites and thicker primary clay layers *on* the bedding surfaces were, in general, seamless.

3. The origin of undulation seams, the cutting of fossils, bedding, and penetration of seams and bedding surfaces, and the branching of seams are all hard to explain by this hypothesis.

4. Concretions, fossils and similar inclusions should produce columns by compression, but such evidence is rare.

5. Shaub's "plastic flows" should make several small involutions in the sediments around the columns, but in general, these features are absent.

6. The agents of the contraction-pressure process are universal so that stylolites would be expected to occur in all horizons and in all kinds of fine-grained bedded sediments, but such occurrences have not been observed.

SUBAQUEOUS-SOLUTION ORIGIN OF STYLOLITES

From the foregoing observations and discussion it is concluded that:

A. The stylolites described by the writer could not have been formed by pressure-solution action in solid rock, but several observations support a solution

origin of the stylolites.

B. Neither the pressure-solution nor the contraction-pressure hypothesis can be used alone to explain these structures. However, a solution to the problem may be obtained by extracting certain ideas from both hypotheses: i.e. *The Stylolites were Formed by Solution in Soft Sediments.*

The striking similarity of stylolites to lapiés which were formed by surface solution of limestones (Stockdale 1922, fig. 19) also suggests this origin for stylolites. Wattenberg (1935, 1936) and others carried out oceanographic studies on the solution of limestone and found that such solution may be caused by changes of pH, temperature, water circulations, etc., and result in temporary and local characteristics.

Certain peculiarities noted in the stylolites investigated by the writer are in accordance with the ideas expressed by various oceanographers. The condition favoring the solution would not always be present, and consequently stylolites are found only in certain horizons of the formations.

For example, the pH of sea water is dependent upon its CO_2 content. In near-surface water, during the time of photosynthesis, the CO_2 ratio is low. In deeper water the pH decreases because of the decomposition of planktonic remains. It is lowest in the near-bottom water in a shallow sea. However, in ocean deeps, which are reached by only a small quantity of organic remains, the CO_2 content is again low (fig. 9). In bottom waters in shallow basins, a periodical enrichment in plankton could lower the pH to a sufficient extent to produce changes in the sediment. Even the smallest local depression of the pH under these conditions would cause some solution of the calcareous mud. Thus the development of stylolite seams could take place two or three times during the sedimentation of one bed. An additional possibility is that the sediment between two seams might be removed, in some places, so that the seams would fuse or penetrate each other.

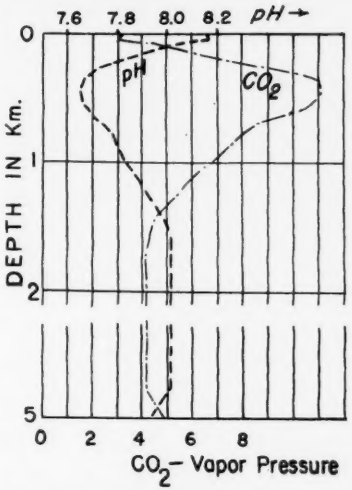

FIG. 9.—The relationship between CO_2 and pH in the middle latitudes of the Atlantic Ocean according to Wattenberg, 1936.

A greater variation in pH would affect larger areas, so that the largest stylolites occur with the largest seams and these are scattered over the widest areas. Because the changes of pH are more or less gradual, stylolites on the margins of seams are smaller. The small turbulent currents in such a dynamic medium as water are very irregular. Such irregularities produce changes either in the form or location and size of columns or they may produce the cutting of fossils, gradation into undulations and other features that characterize stylolites.

Because sea water can attack all surfaces of the columns, an insoluble clay skin remains on both the sides and on the tops of the columns. Curved stylolites, columns with narrowed bottoms, and undulation seams could be produced by the solution of walls, movement of water, and the force of gravity. The striated side surfaces on columns may have originated in a similar way to those on earth pillars. Fossils and concretions may remain as a resistant covering during the

formation of such stylolites similar to the covering of pinnacles. This may explain the relationship between stylolites and fossil coverings and flint concretions (e.g. Bastin 1933; Frye and Scobey 1938).

Many of the seams were developed on the sea floor and were, therefore, parallel to the bedding, but solution could also take place below the sea floor in the mud. The vertical Malm seams and fine sutures which run through the limestone in all directions may have been formed by the latter action. The Malm seams could have been formed by solution along tight fractures in a thin-bedded sediment. The higher anisotropy of sediments in a vertical direction could have caused the sharp ends of Malm columns. The movement and sinking of mud may take place by under-surface solution and this may lead to the development of small faults, microbreccias, involutions, and folds near stylolitic seams (Shaub 1939, 1949).

It is difficult to understand how the fine structure seen in stylolites could be preserved in a soft sediment. However, we know of several very fine structures which were preserved under more or less similar conditions. Ripple and current marks, crystal, rain, or hail impressions, passageways of gasballs, animal trails and others are typical examples. Moreover, the stylolitic clay skin which is rich in colloidal substances may be highly important in the preservation of stylolites.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 22, NO. 4, PP. 221–223
DECEMBER, 1952

FELDSPATHIZED SANDSTONE

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ABSTRACT

A feldspathized sandstone containing 8.6 per cent of K_2O, largely in the form of authigenic orthoclase, is a distinctive lithic unit in the lower part of the Upper Cambrian Franconia formation. The rock is composed of feldspar, 48 per cent; quartz, 44 per cent; glauconite, 5 per cent; muscovite, 2 per cent; collophane, 0.5 per cent; leucoxene, 0.4 per cent; and traces of zircon, tourmaline, and garnet. The chemical and physical properties of the rock are discussed.

INTRODUCTION

A thin-bedded, shaly, micaceous sandstone is a distinctive lithic unit of the Upper Cambrian Franconia formation in southeast Minnesota and west-central Wisconsin. The rock contains nearly 50 per cent of feldspar, largely authigenic orthoclase, and is referred to as a feldspathized sandstone.

The Franconia formation consists of fine- to medium-grained, glauconitic sandstone and has an average thickness of approximately 175 feet. In the lower half of the formation the shaly, feldspathized sandstone forms an easily recognized member that attains a maximum thickness of 30 feet. This unit is the "micaceous shale" described by Twenhofel and Thwaites (1919) in the Tomah-Sparta area of Monroe County, Wisconsin, and was included in the "Goodenough member" (*Conaspis* zone) in the Franconia subdivision proposed for Wisconsin by Twenhofel, Raasch, and Thwaites (1935).

The feldspar content of a Franconia sandstone was first noted by Tester and Atwater (1934) who state that "approximately 30 per cent of the sand is authigenic feldspar in grains $\frac{1}{8}$ to $\frac{1}{16}$ millimeter in size." The sandstone referred to represents a non-shaly, nearer-shore phase of the feldspathized sandstone described here.

DESCRIPTION

The feldspathized sandstone is yellow to light gray, very fine-grained, micaeceous, and laminated. It is characteristically thin bedded with beds 1 to 6 inches thick separated by laminae or partings of gray-green, micaceous shale. In some fresh exposures 1- to 2-inch shale beds are found.

The silty, very fine-grained sandstone shows a distinct maximum in the $\frac{1}{16}$ millimeter grade size with the next most abundant grade being the coarse silt admixture (table 1). The distribution of grains in the larger sizes is only approximate because of aggregates that could not be reduced without an undue amount of fracturing. The interbedded shale consists of approximately equal amounts of silt- and clay-size particles. Hydromuscovite (illite), identified in index oils, is the chief component of the clay.

Trilobite molds are scattered on the bedding planes or clustered in thin, nonlaminated lenses. Excellent specimens

TABLE 1.—*Mechanical analysis of feldspathized sandstone*[1]

Size (Millimeters)	Weight per cent	Constants
$\frac{1}{2}$ to $\frac{1}{4}$	6.8[2]	Md—0.08
$\frac{1}{4}$ to $\frac{1}{8}$	16.2[2]	So —1.44
$\frac{1}{8}$ to $\frac{1}{16}$	40.6	Sk —1.17
$\frac{1}{16}$ to $\frac{1}{32}$	31.1	
$\frac{1}{32}$ to $\frac{1}{64}$	1.8	
Less than $\frac{1}{64}$	3.5	
	100.0	

[1] Sample from Maynard Pass near Tomah, Monroe County, Wisconsin.

[2] Fraction composed largely of muscovite flakes and aggregates of smaller grains.

TABLE 2.—*Chemical, mineralogical, and physical properties of feldspathized sandstone*[1]

Chemical Analysis[2] Weight per cent		Mode[3] Volume per cent		Physical Properties
SiO_2	78.73	Orthoclase ($Or_{98}Ab_2$)	48.0	Grain density (23°/4°)—2.605[4]
Al_2O_3	10.36	Quartz	44.0	
Fe_2O_3	0.66	Glauconite	5.0	Bulk density (24.5°/4°)—1.917[4]
FeO	0.13	Muscovite	2.0	
MgO	0.17	Collophane	0.5	
CaO	0.23	Leucoxene	0.4	Per cent porosity—26[4]
Na_2O	0.14	Zircon	tr	
K_2O	8.60	Tourmaline	tr	Permeability (Millidarcys)[5]
H_2O^+	0.33	Garnet	tr	Parallel to bedding—801
H_2O^-	0.13			Normal to bedding—228
TiO_2	0.35			
P_2O_5	0.19			
CO_2	0.01			
MnO	0.01			
	100.04			

[1] Sample from near Brownsville, Houston County, Minnesota.
[2] James J. Engel, analyst.
[3] Calculated by R. R. Berg, tr = 0.1 per cent or less.
[4] Determined by S. S. Goldich.
[5] Determined by Wesley Danielson.

were collected from the feldspathized sandstone, and good preservation as well as ease of collecting are due largely to the coherence and flaggy character of the rock.

COMPOSITION

Chemical and mineralogical analyses of the feldspathized sandstone are given in table 2. The mineralogical composition is based on frequency percentages obtained by point count (Chayes, 1949) in thin section. Because the fine grain size of some of the material made positive identification in thin section uncertain, the percentages were adjusted to conform with calculations from the chemical data.

Potash was distributed according to the relative amounts of the potassium-bearing minerals determined in thin section. Modal feldspar makes up 48 per cent of the rock by volume. Although a few detrital grains of microcline were noted in thin section, authigenic feldspar greatly predominates and occurs as rhombic overgrowths on detrital grains and as cement interstitial to the quartz grains. The authigenic feldspar is thrown into conspicuous negative relief by reducing the light with a substage diaphragm. Soda-plagioclase could not be identified, and the composition $Or_{98}Ab_2$ given in table 2 is an adjustment to account for the small amount of soda recorded in the chemical analysis. The purity of the authigenic feldspar is striking. Feldspar with authigenic overgrowths separated from the New Richmond sandstone from Lake City, Minnesota and analyzed by Goldich (1934) contains a somewhat larger component of sodic feldspar, approximately 7 per cent, but detrital grains account for a larger proportion of the total feldspar in the New Richmond sandstone.

Glauconite is not as abundant in this rock as in other Franconia sandstones. A minimum value of 4 per cent is indicated by point count, and the amount of 5 per cent given in table 2 fits the chemical data. In the calculations the structural formula, $(OH)_8K_2(Mg, Fe'')_3(Fe'', Al)_6(Si_{14}Al_2)O_{40}$, given by Gruner (1935)

was used. Detrital grains are subspherical, light yellow-green to dark green with irregular lobate surfaces often marked by cracks, and these grains account for the 4 per cent determined by point count. In addition, some muscovite grains show light-green fringes or contain fine, granular aggregates of glauconite, so that the total estimate of 5 per cent from calculations is reasonable.

Muscovite is conspicuous in hand specimens although it makes up only 2 per cent by volume. Most of the muscovite grains are clear and unaltered, and flakes oriented parallel or slightly inclined to the laminations are the largest detrital grains seen in thin section.

Quartz constitutes 44 per cent of the volume and occurs in subangular to subrounded grains. Collophane, estimated at 0.5 per cent, is present as fragments of inarticulate brachiopods. The relatively large amount of titania, 0.35 per cent, is accounted for largely by leucoxene, but brookite is abundant in heavy mineral fractions of some samples. Garnet, tourmaline, and zircon grains are small and well rounded. Zircon is generally most abundant, but none of these detritals exceeds 0.1 per cent.

CLASSIFICATION

The proportions of quartz and feldspar in this sandstone are those of arkose. The term, however, is properly used to describe a rock containing detrital feldspar and therefore is not applicable. The name feldspathized sandstone serves to emphasize the origin and adequately describes the rock.

ORIGIN

The feldspathized sandstone was deposited in a marine environment of quiet, shallow water. Muds and clayey to silty sands accumulated, and during lithification mineralogical changes took place. Authigenic orthoclase was formed in the sandstone and hydromuscovite (illite) developed in the shale. The original sediment contained a small amount of detrital feldspar which served as nuclei for precipitation of orthoclase overgrowths, but at the same time authigenic crystals formed in the pore spaces and filled the interstices between the detrital quartz grains. Clay minerals originally deposited with the clastic quartz and feldspar probably provided a large part of the alumina and silica, and sea water supplied the potassium.

The porosity of the feldspathized sandstone calculated from determinations of grain and bulk density (table 2) is 26 per cent. The trilobite molds formed by interstratal solution of the carapaces probably accounts for most of the voids. Thin sections show that the feldspar cement is truncated on the margins of fossil molds, indicating that the feldspar was formed before solution of the carapaces.

ACKNOWLEDGMENTS

I am indebted to S. S. Goldich for his active interest in this study. The Minnesota Geological Survey, through G. M. Schwartz, Director, provided funds for the chemical analysis made in the Rock Analysis Labroatory of the University of Minnesota.

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FIGS. 1–4, DECEMBER, 1952

RECENT HISTORY OF A SAND SPIT AT SAN NICOLAS ISLAND, CALIFORNIA[1]

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ABSTRACT

At the eastern end of San Nicolas Island a low triangular sand spit occurs. Changes in the configuration of the spit during the last one hundred years demonstrate that it is unstable. In the spit, sand has been supplied primarily by an east-flowing longshore current which moves along the northeastern coast of the island.

INTRODUCTION

San Nicolas Island, eight miles long and three miles wide, is sixty miles off the mainland of southern California (fig. 1). The long axis of the island is northwest-southeast, in the prevailing wind direction of the region. A low sand spit at the southeastern end has formed in response to wind and current. Charts and photographs made during the last century show that the spit has changed outline markedly on at least two occa sions.

GENERAL CHARACTERISTICS OF THE SPIT

The spit is a sand feature roughly triangular in shoreline, with the southern side more concave than the northern. The deposit is over two miles long and at low tide the spit point is about one mile from the main island mass. The submerged portion is sinuous in plan and about a mile long. Waves approach the submerged segment from northwest and southeast and crash against one another —a most spectacular sight during periods of heavy swell. Width of the spit increases from a few feet at the tip to nearly half a mile at the island. Approximately half the spit is from 5 to 15 feet above low water. On the southern side nearest the island a shallow lagoon develops occasionally. The lagoon is completely cut off from the sea by a bar (fig. 2) and is filled only by occasional high waves from the south.

[1] Contribution from the Scripps Institution of Oceanography, new ser., no. 585.

CHANGES DURING THE LAST CENTURY

In 1847, Kellett described a line of breakers extending a mile and three-quarters from the eastern end of the island. It therefore appears probable that the spit had, at that time, a configuration similar to that which it has today. In 1851 the first accurate chart of the area was published by the United States Coast and Geodetic Survey. This chart does not show a spit, but instead a rounded sandy area farther northwest (fig. 3). Despite the fact that this survey was published on a scale of 1:380,000, it is unlikely that a feature as prominent as the present-day spit could have been missed. The first detailed survey of the island was made in 1879 by the U. S. Coast and Geodetic Survey. The modern spit was not then in existence (fig. 3); on the contrary, the large, rounded sandy protruberance first indicated by the 1851 survey is shown in considerable detail. In 1879 several sounding lines across the area now occupied by the spit show water depths of two to seven fathoms. This striking change, which evidently occurred between 1847 and 1851, has caused Davidson (1889) to remark:

"... (Kellett) ... also lays down breakers for a mile and three-quarters from the eastern point. It is probable that he has been misled by heavy current rips conflicting with the westerly swell; or it is possible there may

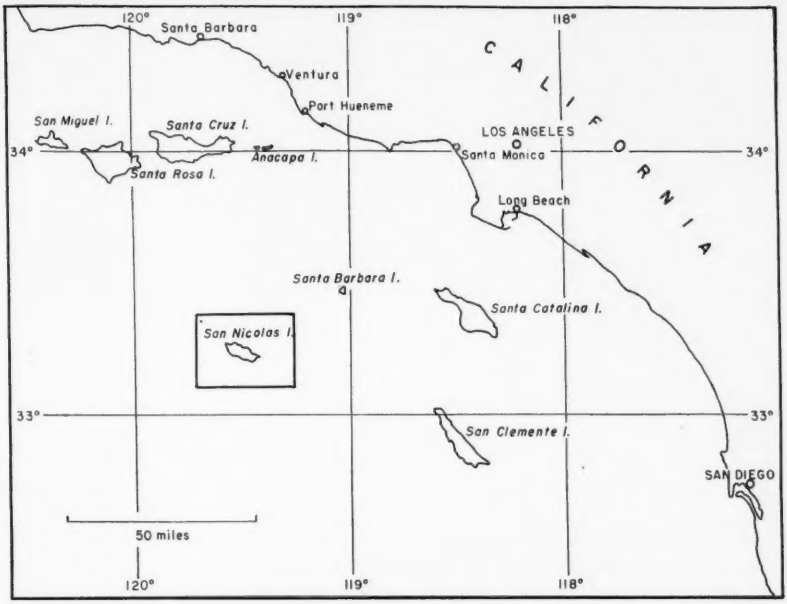

FIG. 1.—Outline map of southern California showing the location of San Nicolas Island.

be some hidden dangers in the kelp-field off the eastern end of the island . . . ."

Davidson, in the 1889 edition of the Pacific Coast Pilot, describes conditions as of that date:

" . . . The eastern end of the island is one and one-quarter miles broad, high and bold, except at the northeast point, where there is a low sand spit stretching out one-third of a mile, and around which the currents run at times with great force . . . ."

Doubtless, Davidson referred to a feature like that shown on the 1879 chart (fig. 3), for the modern spit is not located at the northeastern extremity of the island, is much longer than a third of a mile, and currents certainly do not run "around" it. (The spit is pointed at its eastern end and a current would have to change direction nearly 180° in a very short distance in order to run "around" it.) Holder (1910) mentions: ". . . the long attenuated sand spit . . ." indicating that the present-day configuration had been attained by 1910.

A second detailed U. S. Coast & Geodetic chart was made in 1925, and a third in 1932. Airplane photographs were taken, in 1943 by Fairchild Aerial Surveys, Inc., in 1945 and 1950 by the United States Navy Electronics Laboratory, and in 1950 by the United States Marine Corps. Charts and photographs all show a long attenuated sand spit, differing only slightly in each case. These are compared in figure 3. The history of the sand spit suggests the feature is in delicate adjustment with its environment. Approximation of the volume of sand in the spit from 1851 to 1879 compares favorably with that of the present spit if it is assumed that the amount of sand below low water was the same in both cases. Unusual wave action from the south may have been responsible for the northward shift between 1847 and 1851.

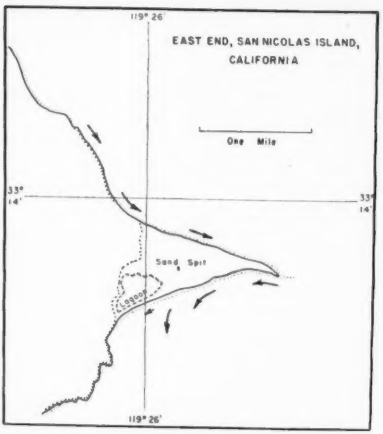

FIG. 2.—Detail of San Nicolas sand spit showing location of the lagoon and the direction of prevailing longshore currents.

Weather records do not extend far enough to show if the 1851 to 1879 position was maintained by more or less unusual wave activity from the south or whether the southward shift between 1879 and 1910 can be attributed to unusual waves from the northwest. In either case, it appears that the volume of sand in the spit is nearly static and that the feature moves as a unit.

SOURCE AND DEVELOPMENT OF THE SPIT

Wind plays a significant rôle in the maintenance of the spit, yet the spit is not primarily wind-formed. Prevailing winds are northwesterly and often blow vigorously for days at a time. Bottles and glass fish-net floats stranded on the spit are commonly sand-blasted on their windward sides and completely unaffected to the leeward. Low, parallel ridges of loose shifting sand lie obliquely across the spit, formed by winds blowing across, rather than parallel, to the spit. Troughs between these ridges are often covered with shell "pavement." Wind and surf, acting in concert, have heaped sand as much as 15 feet above low water. Locally, the process has been assisted by jetsam which holds some of the sand in place. Winds blowing parallel to, or approaching the northeast coast at a slight angle should produce a well-defined longshore drift. The southern coast, on the other hand, is parallel to prevailing wind direction only in its western half; the eastern half of the southern coast normally lies in the lee, and longshore drift is apt to be weaker there. Northwesterly winds have the least effect where the south side of the spit joins the main mass of the island. Here, the island rises boldly some six-hundred feet and protects the shore from all but the strongest winds.

Current measurements made along the northern coast confirm the existence of a strong longshore drift toward the spit (0.2 to 0.3 knot during a period of low waves). Near the outer extremity of the northern side of the spit, waves approached (March 1951) at an angle which should have developed a northwest-flowing current in opposition to the wind. The fact that this did not occur indicates that longshore drift established along the northern coast of the island had sufficient velocity to overcome opposing wave approach near the end of the spit. During a period of southern swell (March 1951), currents measured along the southern side of the spit moved westward toward the island, turning away from shore near the mid-point of the spit (fig. 2). This current and the one on the north side of the spit evidently act to maintain the *status quo* by carrying excess sand into deeper water.

The spit is believed to be primarily the product of sand drifted along the northern coast of the island for the following reasons:

(1) Longshore drift is well-developed along the northern coast and acts in the proper direction. Further, the northern side of the spit is nearly a continuation of the north coast beaches, whereas the southern side is offset from the general trend of the southern coast, and is separated from the southern beaches by a large rocky headland (fig. 3).

(2) Longshore drift on the southern

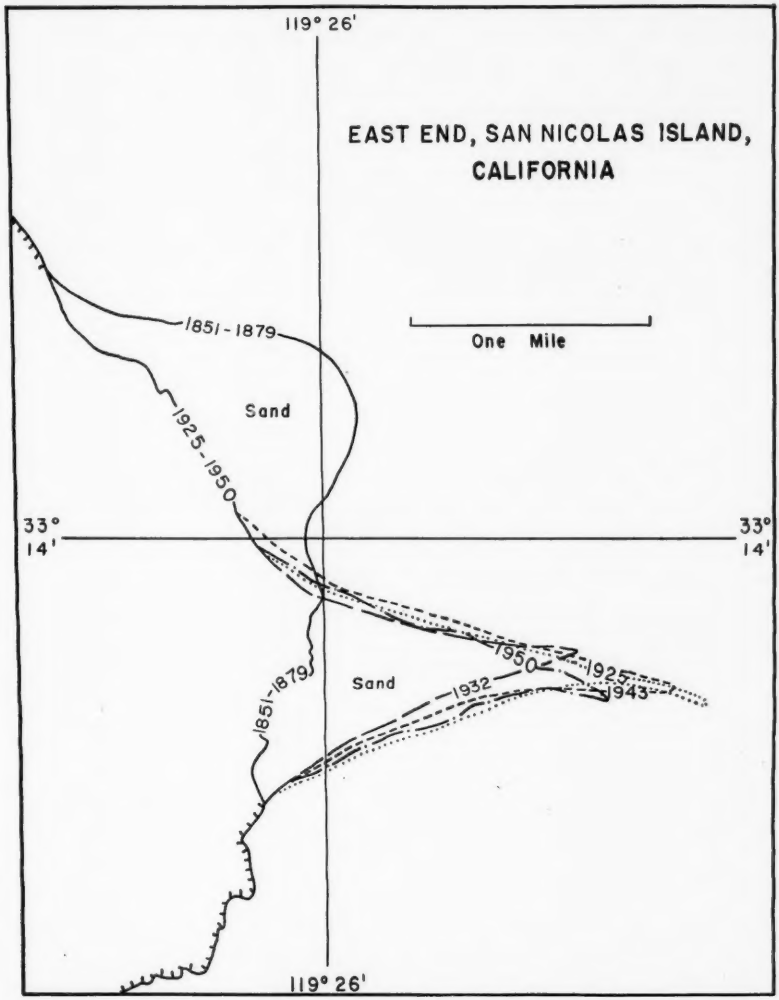

FIG. 3.—Outline map illustrating the changes in the configuration of the sand spit from 1851 to 1950.

coast is less strongly developed and has been observed to move *toward* the island along the south side of the spit.

(3) Sand transported by wind across the top of the island is of minor quantitative importance. Winds blowing across the top of the island carry considerable sand in the western part; dunes and sand hillocks are gradually moving eastward from this area. When winds reach the

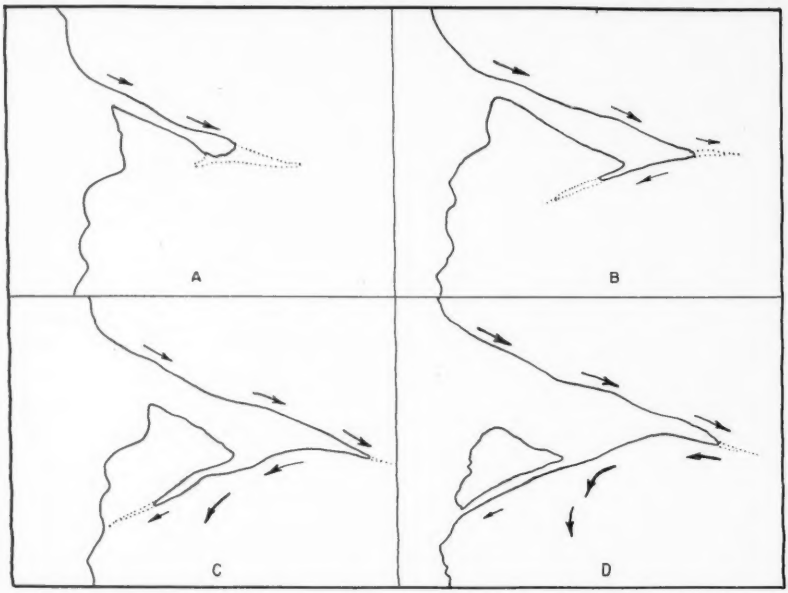

FIG. 4.—Diagram illustrating a possible mode of formation for the San Nicolas sand spit.

eastern end of the island, however, most of their sand load has been dropped, and, owing to the grass cover on the eastern two-thirds of the island, little new load has been acquired.

(4) The position of the spit between 1851 and 1879 shows an even closer relation to the north coast than at present.

CONCLUSIONS

The bulk of material appears to have reached the spit along the northern coast, but the present form has been influenced by the west-flowing current along the south side of the spit. Figure 4 illustrates the development of the present feature as deduced from the currents. The northern side of the spit is a coast of wave deposition and wind erosion, and the outer end of the southern shore is a coast of wave erosion and wind deposition. The inner part of the south side of the spit is most probably a wave deposited bar.

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FIGS. 1–2, DECEMBER, 1952

STUDY OF THE DISPERSING AGENTS[1]

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ABSTRACT

On studying various dispersing agents it was found that sodium hexametaphosphate and sodium tetraphosphate are the most effective deflocculants. The dispersing characteristics of other chemicals like sodium pyrophosphate and sodium acid pyrophosphate approach sodium hexametaphosphate very closely and the deciding factor in choosing one of them for laboratory use should be that of economy and price of chemical. The amount of polyphosphate required for maximum effect varies from 0.025 to 0.06 grams per 100 cc of thick suspensions.

The desirability of finding some chemical which will prevent flocculation of suspensions high in organic and electrolytic content has been felt for a long time. Several solutions of this problem are offered in the present work.

INTRODUCTION

When an average clay or marine mud is suspended in moderately pure water, it usually flocculates. This flocculation is caused by neutralization of the negative charges on the clay particles. Outstanding among the many factors that have flocculating effect are the presence of electrolytes. The present research was conducted for the purpose of investigating relative effectiveness of various dispersing agents and finding such treatment which will eliminate the necessity of filtering samples high in electrolytic content.

Complex phosphates and tanstuffs which are the most effective dispersing agents are capable of yielding spatially extensive anions which plate the clay particles. The complete plating of all the clay particles yields maximum deflocculation, due to the fact that particles on gaining more negative charges repulse each other with greater strength.

CLASSIFICATION OF DISPERSING AGENTS AND MECHANISM OF DEFLOCCULATION

The average muds and clays when suspended in moderately pure water are generally in an incompletely deflocculated state. Clays which are not self-peptizing, such as most calcium clays, are found to settle out when an attempt is made to prepare a suspension from them. The average newly made suspension can be deflocculated and the measure of deflocculation in the ordinary case of thick suspensions is the reduction in viscosity caused by the addition of deflocculating agents. Those in common use or of interest chemically are divided into four groups:

Group I

1. Sodium hydroxide
2. Sodium carbonate and bicarbonate
3. Sodium silicate
4. Sodium oxalate
5. Sodium orthophosphate (mono-, di- and tri-)

Group II

1. Molecularly dehydrated phosphates, such as:
   a) Sodium pyrophosphate ($Na_4P_2O_7$ and $Na_2H_2P_2O_7$)
   b) Sodium polymetaphosphate $(NaPO_3)_N$
   c) Sodium triphosphate ($Na_5P_3O_{10}$)
   d) Sodium tetraphosphate ($Na_6P_4O_{13}$)
2. Vanadium analogs of the above such as:
   a) Sodium pyrovanadate ($Na_4V_2O_7$)
   b) Sodium polymetavanadate $(NaVO_3)_N$
3. Thiotetraphosphates such as: Sodium trithiotetraphosphate ($Na_6P_4O_{10}S_3$)
4. Borophosphates, -vanadates, -tungstates and the like, such as: Sodium borophosphate glass $[(NaBO_3)_X(NaPO_3)_Y]_N$

[1] Contribution no. 105 of the Allen Hancock Foundation, The University of Southern California.

5. Esters of molecularly dehydrated phosphoric acids
6. Alkali—metal phytates

Group III

1. Tannic acid
2. Quebracho extract
3. Chestnut extract
4. Gallic acid
5. Mimosa extract
6. Pecan extract ("Kandu")
7. Coffee
8. Urundy extract

Group IV

1. Starch
2. Quince seed
3. Locust bean seed
4. Iranian and Indian gums such as:
   a. Shiraz
   b. Ghatti
   c. Tragacanth
   d. Karaya
   e. Arabic

Generally speaking, deflocculants of the first group are only occasionally effective, and then only over a short range of concentration, excessive additions rapidly bringing about flocculation. As may readily be seen they comprise either alkalies or simple compounds which form insoluble calcium and magnesium salts. Naturally those deflocculants forming highly insoluble calcium salts are effective particularly in cases where flocculation is due to the presence of Ca^{++} ion. The dispersing action of NaOH is apparently due to adsorption of the OH^- ions on the clay particles. Figure 1, which is based on experimental results obtained by the investigator, shows that the cataphoretic velocity of the clay particles increases with increased concentration of NaOH. This effect is decreased with the greater concentrations of NaOH, probably because unsaturated bonds of kaolinite clay particles are eventually satisfied on addition of OH^- ions.

When the addition of this electrolyte is carried beyond the range indicated, a

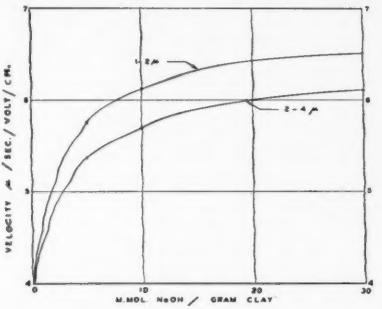

FIG. 1.—Velocity of clay particles toward positive electrode versus amount of NaOH added.

flocculation of the system results because the excess influx of Na^+ ions results in the neutralization of OH^- ions adsorbed on the clay particles. These results are in close accord with those of Coughanour and Utter (1944).

The deflocculants in the second and third groups are characterized by effectiveness at much lower concentration than those in the first group, as well as by much greater ultimate deflocculation. The following peculiarities of these groups are helpful in understanding the mechanism of deflocculation:

1. Certain of the phosphates have calcium sequestering properties. While calcium sequestering power does not appear to be a necessary prerequisite for powerful clay deflocculant action, nevertheless it will certainly enhance any deflocculating power otherwise possessed by a compound; at least to the extent to which such compounds as sodium carbonate and sodium oxalate are effective.
2. Considering the structural configuration of triphosphoric acid and tannic acid, one is struck by the fact that these are capable of yielding spatially extensive anions, in which, in the ionized state, the negative charge is rather more uniformly distributed along the extent of the molecule than is the case, for example, in the orthophosphate or car-

bonate ion (even when the latter is fully ionized, which requires a high pH.) Hence complex phosphates and tanstuffs "plate" the clay particles. The complete plating of all the clay particles yields maximum deflocculation due to the repulsion of clay particles which have like charges.

3. The fact that even the simpler of the molecularly dehydrated phosphates probably yield anions of higher charge than those compounds of the first group, because of the apparently higher dissociation constants of the former, adds to the general picture of a "platable" polyvalent anion. For example, the dissociation constants of pyrophosphoric and orthophosphoric acid are as follows:

$H_4P_2O_7$: $10^{-0.85}$, $10^{-1.96}$, $10^{-6.59}$, $10^{-8.44}$
H_3PO_4: $10^{-1.96}$, $10^{-6.7}$, $10^{-12.4}$

If the pH is around 8.5 to 10, it can be seen that any soluble pyrophosphate will be largely ionized to give $P_2O_7^{----}$ ions, while an orthophosphate will give HPO_4^{---} ions.

Tanstuffs require a higher pH for maximum effectiveness, which is no doubt related to the fact that they are weaker acids than the complex phosphates. However, tanstuffs have the advantage over polyphosphates due to the fact that they are not rendered inoperative in excess of Ca^{++} ion.

The deflocculating effect of group IV, which consists of starch and water soluble gums, is due to the protective action of these substances. The stabilizing action of protective colloids is due to the formation of a protective coating on the particles, giving rise to a hydrophilic dispersion where each particle has an insoluble nucleus. However, one of the disadvantages of this group is the fact that it increases the viscosity of the dispersion to a certain extent. Possibility of fermentation is even a bigger disadvantage, which can be prevented, however, by one of the following methods:

a. Maintaining high pH ($\approx$11.5)

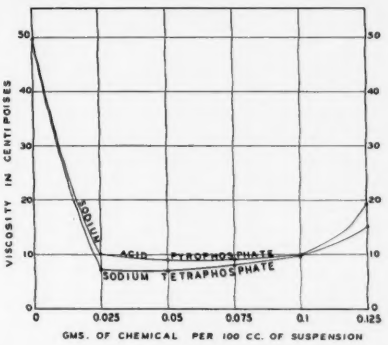

FIG. 2.—Viscosity of suspension versus per cent chemical used.

b. Concentrated salt solutions
c. Use of anti-bacterial agents like paraformaldehyde.

EXPERIMENTAL RESULTS

In order to arrive at the best dispersing agents from the polyphosphate group and the quantity required for maximum amount of deflocculation, a series of tests were made with the best available polyphosphates. The list of these compounds and their formulae is shown in table 1.

TABLE 1.—*Polyphosphate dispersing agents and their formulae*

Compound	Formula
Sodium hexametaphosphate	$(NaPO_3)_6$
Sodium tetraphosphate	$Na_6P_4O_{13}$
Sodium acid pyrophosphate	$Na_2H_2P_2O_7$
Tetrasodium pyrophosphate	$Na_4P_2O_7$
Tetrapotassium pyrophosphate	$K_4P_2O_7$
Sodium tripolyphosphate	$Na_5P_3O_{10}$

Different percentages of dispersing agents were added to thick suspensions of montmorillonite and illite clays. The amount of dispersing agent was measured in grams per 100 cc of suspension. After each addition the samples were vigorously stirred and the viscosity determined in centipoises with stormer viscosimeter. Due to the fact that reduction

in viscosity is the measure of deflocculation, it is possible to evaluate each polyphosphate on a comparative basis. Figure 2 shows the dispersing effect of sodium tetraphosphate and sodium acid pyrophosphate on thick suspension of montmorillonite clay having 50 cp. viscosity.

Figure 2 is typical of all other polyphosphates. The amount of polyphosphate required for maximum reduction of viscosity varied from 0.025 to 0.06 grams per 100 cc of mud, which in all cases corresponds to 0.0001 mols. As the number of PO_4 radicals per molecule increases, the reduction in viscosity increases, with sodium hexametaphosphate producing the most rapid reduction in viscosity.

A very important point should be kept in mind while adding polyphosphates. Addition of electrolyte results in flocculation due to the neutralization of negative charges on the clay particles. On adding polyphosphates, which are also electrolytes, the flocculating effect is only delayed. Therefore, great care should be exercised on controlling the amount of polyphosphate necessary to achieve optimum results. If a certain limit is exceeded an adverse result is obtained.

The possibility of finding some dispersing agent which will eliminate the necessity of filtering samples high in organic and electrolytic content has been investigated too. A sample of mud, which was black due to the presence of organic matter, has been obtained from the channel deposit of Newport Bay, California (depth of one foot). Five one-liter suspensions were prepared from tap water and 20 grams of this sample. Without treatment samples flocculated within a few minutes.

Table 2 shows the dispersing effect of different treatments.

Partial flocculation on using starch is probably due to the fact that starch tends to flocculate montmorillonite clay while dispersing kaolinite and illite.

The use of Quebracho with NaOH presents a possibility of eliminating tedious process of removing organic matter and filtration in order to attain complete deflocculation. Sodium hexametaphosphate which is successfully used as a deflocculant in the University of Southern California, can be used in some cases without filtration of the sample. However, this chemical is not effective without previous filtration if the sample has high electrolytic and organic content.

TABLE 2.—*Effect of different treatments on Newport Bay sample at the end of three days*

Dispersing agent	Amount gm/1000 cc	Results
Quebracho + NaOH	4 + 2	Complete deflocculation
Starch	6	Some flocculation
Gum Ghatti	6	Complete deflocculation
Sodium hexametaphosphate	2.48	Flocculation

REPRODUCIBILITY OF RESULTS OBTAINED WITH PIPETTE ANALYSIS ON VARYING THE DISPERSING AGENTS

In order to determine the effect of different dispersing agents on the mechanical analysis of sediments obtained with the pipette analysis, the size distribution of marine mud from San Pedro Basin, California, has been determined using various dispersing agents. The results are shown in table 3.

CONCLUSIONS

The most effective dispersing agents from the polyphosphate group are sodium hexametaphosphate and sodium tetraphosphate. The dispersing capacity of some other chemicals like sodium pyrophosphate and sodium acid pyrophosphate approach sodium hexametaphosphate very closely, and, therefore, the deciding factor in choosing one of them for laboratory use should be that of economy and price. The amount of polyphosphate required for maximum effect varied from 0.025 to 0.06 grams per 100 cc of suspension, which in all cases cor-

TABLE 3.—*Size distribution of marine mud from San Pedro Basin determined with different dispersing agents*

Diameter in millimeters	Weight per cent of size groups			
	Filtration +sodium hexameta-phosphate .248 gm/1000 cc	Sodium acid pyrophosphate 1 gm/1000 cc	Gum Ghatti 5 gm/1000 cc	Quebracho 5 gm/1000 cc +NaOH 1 gm/1000 cc
0.031–0.062	15.2	13.5	15.8	12.0
0.016–0.031	10.4	9.4	11.0	9.0
0.008–0.016	12.4	13.1	12.8	10.0
0.004–0.008	13.0	12.0	13.9	15.0
0.002–0.004	11.2	10.6	13.5	11.9
0.001–0.002	7.0	12.4	13.0	13.1
<0.001	30.8	29.0	20.0	29.0

responds approximately to 0.0001 mols.

Complete deflocculation of samples high in electrolytic and organic content can be attained by the use of several dispersing agents, without a tedious process of removing organic matter and filtration. Quebracho, with some NaOH, was found to be the most effective dispersing agent for this purpose.

ACKNOWLEDGMENTS

The investigator is greatly indebted to Dr. K. O. Emery and Professor D. H. Larsen whose help was invaluable in carrying this work to completion. Part of the theory on mechanism of deflocculation is based on the lecture notes of Professor D. H. Larsen.

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FIG. 1, DECEMBER, 1952

SELENITE CRYSTALS IN THE CLAYS OF GREAT SALT LAKE

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University of Utah

ABSTRACT

Selenite crystals 2 to 6 inches in length have recently been found in a few places around the shores of Great Salt Lake in the soft sodium clays of the lake bottom. This occurrence may be significant in explaining the origin of selenite crystals in shales, so commonly seen on the erosion surfaces of shale formations in arid regions. Since the lake waters are impoverished in calcium ions, the selenite crystals have never been precipitated in historical times and are not believed to be a precipitate from the lake waters in times past. Bacteria may be the cause of a steady state in the clays conducive to the growth of the gypsum crystals, and physical changes incident to the consolidation of the clays may also be significant.

OCCURRENCE IN GREAT SALT LAKE

Selenite crystals occur in the soft clays around the shores of the Great Salt Lake and suggest the origin of selenite crystals in various shale formations of geologic antiquity. The locality especially known for the selenite crystals is Rozell Point on the north shore of the lake, west of the Promontory Range peninsula. They have also been reported from the shore west of Salt Lake City and Farmington, but these latter occurrences have not been investigated by the writers.

Rozell Point is about ten miles south of the abandoned town site of Promontory and is underlain by interbedded basalt and travertine of mid-Tertiary age. The clays that flank the "point" have been described by Eardley (1938, p. 1334–1359). They are very plastic and sticky sodium clays composed of 10 to 25 per cent calcium and magnesium carbonate and 90 to 75 per cent silt and clay sized particles in about equal proportions. They are singular among all Great Salt Lake clays sampled in that they have the highest amount of magnesium carbonate relative to calcium carbonate. The relatively large amount of magnesium is not believed to be particularly significant to the growth of the gypsum crystals, however, because they occur elsewhere in clays of far less magnesium content.

The clay is part of the sediment of the bottom of Great Salt Lake. It has been accumulating in the near shore zone of very shallow water, but since the drought of 1932–35, it has been mostly exposed to the air. It remained completely saturated, however, and is now nearly covered with the lake's brine again.

The crystals occur in clusters or "pockets" a few inches to 18 inches below the surface of the lake sediments. Figure 1 is a sketch of the occurrence of the gypsum crystals by Professor Junius J. Hayes of the University of Utah who conducted a collecting party of about 55 people to Rozell Point. The larger crystals, which are somewhat tabular and 2 to 6 inches in diameter, are in a vertical or near vertical position. The smaller crystals may have a more irregular orientation but they too are believed to approach the vertical in growth position. Of the small crystals that seem concentrated at the top of the clay lens, many are twins or intergrowths and orient themselves at all angles to the horizontal.

CRYSTALLOGRAPHY

The monoclinic gypsum crystals in the Great Salt Lake clays have the negative hemi bipyramid form (111) particularly well developed on all specimens observed. The clinopinacoid (010) is usually very small, but is present on all specimens. On casual observation, the prism (110) appears to be present only

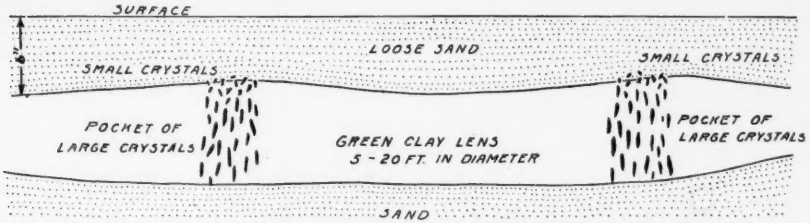

FIG. 1.—Cross section showing the occurrence of gypsum crystals in the clay at Rozell Point, Great Salt Lake. The large crystals are all vertical or nearly vertical, and range from 2 to 6 inches in diameter and ¼ to 1 inch thick. At the top of each pocket of crystals, and near the top of the clay lens is a cluster of small crystals, many of which are twins or intergrowths.

on a few specimens, but close inspection reveals that this face is present on all crystals. It is very small but is a definite controlling factor in the development of the shape of crystals. Cleavage parallel to (010) is so perfect that unusual care must be exercised when handling the specimens in order not to split them. Washing in fresh water often causes them to cleave. Most of the crystals are elongated parallel to the *a* or *b* crystallographic axis. All of the crystals collected show a subsmooth surface in the general position of the clinodome (023), orthodome (103), or basal pinacoid (001), but no smooth surface in this position is recognizable as a crystal face. This subsmooth surface ranges from slightly convex to nearly flat to strongly concave. The majority of the crystals appear nearly equidimensional and rather pancake in shape.

ORIGIN

The discovery of gypsum crystals in the Great Salt Lake clays was unexpected because gypsum or anhydrite has never been precipitated on the lake bottom, at least as far as anyone has observed. The lake waters are impoverished in calcium ions because of the copious precipitation of $CaCO_3$. An abundance of sulfate ions exist, but the first sulfate compound to reach saturation upon concentration by evaporation and cooling of the lake waters in the fall and winter is $Na_2SO_4 \cdot 10\ H_2O$. This is the mineral mirabilite (see Eardley, 1938, p. 1322).

If the chemistry of the lake waters precludes the precipitation of calcium sulfate, what are the conditions in the bottom clays which in places nourish the growth of gypsum crystals? Physical chemists consulted believe that if the bottom clays are bathed by the lake water, they will be part of the same chemical system as the waters, down to a depth of a few inches, at least, and be in equilibrium with them. The base exchange relation of the clays and the water as recounted in a study of the lake clays (Eardley, 1938, p. 1334) supports this conclusion. It would seem that some extraneous influence must be affecting the clays where the gypsum crystals grow. It may also be concluded that for the growth of gypsum crystals up to 6 inches in length and breadth and one inch thick, that the extraneous influence should be slow and steady, driving the reaction in one direction.

Three possible causes of the steady state in the bottom clays of Great Salt Lake seem worth considering. One is the action of spring or seep waters emerging from below and permeating into the clays. Inasmuch as springs or seeps are not recognizable at the places where gypsum crystals are known to occur, the theory seems to lack support. At the Saltair occurrence, the closest mountains are 6 miles distant, the surface flat for miles around, and the sediments below the surface, as far as we know, fairly fine. Such

a setting would not be very conducive to the rise of ground water where the crystals occur.

A second theory of the growth of gypsum crystals in the clays of Great Salt Lake is based on the physical changes that occur as the lake clays lose water and compact. Chemical analyses show that an excess of CaO over the amount necessary to satisfy the CO_2 exists in amounts of a trace to 5.32%. The usual excess amount is about 2%. The excess of MgO ranges from 1.64 to 3.72%. Is it possible that Ca ions are released in the consolidation process? In the absence of data pertaining to the problem, nothing more can be said than to ask the question at present.

The third theory involves the presence of bacteria in the clays and their activity in producing a steady state conducive to the growth of the crystals. It has been observed that bacteria are everywhere very abundant in the clays (Eardley, 1938, p. 1331). Viable bacteria in the clay range from a few hundred to several hundred thousand per wet gram of sediment. Fetid odors about the shores come from bacterial action in the decomposition of blue-green algae that have drifted into the shore, and from the organic matter in the clays themselves.

Professor Claude E. ZoBell of Scripps Institution of Oceanography writes in correspondance about the problem as follows:

"Although I have never been concerned with the precipitation of gypsum in Great Salt Lake, there are good reasons for believing that bacteria may contribute to the process, because nearly all of the bottom samples that I have examined have been found to contain large numbers of physiologically versatile species.

"Sulfate-reducing bacteria have been found to be quite abundant in Great Salt Lake sediments. Under certain conditions such bacteria tend to dissolve gypsum or anhydrite, but in localized environments, as on a crystal surface, the destruction of sulfate ions creates a more alkaline condition there which may promote the precipitation of calcium sulfate from solution:

$$Na_2SO_4 + 8H \rightarrow Na_2S + 4\ H_2O$$

Whether the reaction takes place with the formation of alkaline Na_2S is, primarily, a function of the source of the hydrogen required for the reaction. Some hydrogen sources (such as carbohydrates, for example) may be oxidized by sulfate reducers to give acidic end-products, whereas the oxidation of lactic acid would make the environment more alkaline."

"Another type of bacterial reaction that might result in the precipitation of calcium sulfate, is one resulting in the utilization of carbonate or CO_2. Without writing all of the intermediate equilibrium reactions, the resultant reaction would be:

$$CaCO_3 + 4H + Na_2SO_4 \rightarrow CaSO_4 + (CH_2O) + 2NaOH$$

where (CH_2O) represents the primary building block of bacterial protoplasm. I have found both aerobic and anaerobic autotrophs in Great Salt Lake sediments which utilize CO_2 or carbonate as a source of carbon, but we have not established that these particular bacteria precipitate calcium sulfate."

"A third type of reaction that could result in the precipitation of calcium sulfate is the bacterial oxidation of H_2S in localized environments. Bacteria which oxidize H_2S to sulfate are quite common in nature, although I am not aware of such bacteria having been found in Great Salt Lake. In a solution already saturated with Na_2SO_4 and $CaCO_3$, the addition of sulfate ions in a high pH environment could be expected to result in the precipitation of some calcium sulfate.

"Fourth, the microbial assimilation of phosphate may tend to precipitate calcium sulfate from a solution saturated with sodium sulfate and certain calcium salts. All bacteria assimilate phosphate.

"There are also other microbial reactions that may influence the precipitation or dissolution of calcium sulfate.

The algebraic summation of several such reactions would determine the direction of the reaction. While I do not know that bacteria are responsible for the formation of gypsum crystals in Great Salt Lake sediments, I believe they contribute to the process."

Another line of investigation suggested by Professor Louis P. Gebhard of the Department of Bacteriology of the University of Utah concerns the heat that the bacteria evolve, and the effect of elevated temperatures on solubilities. If the bacteria are numerous and active, the temperature of the clay that holds them will be elevated. Now, the solubility of calcium sulphate in the form of anhydrite in 100 parts of water at zero degrees is 0.1759 parts, whereas at 100 degrees it is a little less, namely: 0.1619. The solubility of gypsum is 0.241 at zero degrees and 0.222 at 100 degrees. For each form of calcium sulphate, the solubility is decreased about 8% as the temperature rises from zero to 100 degrees centigrade. If this solubility variation is not changed by the presence of other salts in solution, then it seems possible that with elevated temperatures the solubility of calcium sulfate would be decreased in the clays, and that gypsum crystals might grow. No temperature measurements have been made of the clays and adjacent water, as far as known so this aspect of the bacteria problem must also be left unsolved.

RECRYSTALLIZATION

Selenite crystals lying on the barren shale slopes of arid regions and reflecting flashes of sunlight to the passerby are very common. It would seem that these crystals were once enclosed by the shale and remain as residual fragments as the soft shale is eroded away. In the memory and experience of the writers and others queried, the main cleavage face (010) of these crystals is parallel to the tabular shape of the crystals. However, in the crystals from Great Salt Lake, the cleavage is normal to the flat dimensions. This suggests that after original growth in the bottom clays, recrystallization takes place.

The theory of crystal growth which relates to the final shape of a crystal may be briefly stated as follows: if a crystal is allowed to grow freely in all directions, uninhibited by confinement or differential pressures, the final shape will be determined by the rate of growth of each crystal face, and the fastest growing face eventually eliminates itself as a prominent form of the crystal. Hence, in any crystal it can be deduced which face grew fastest by its proportional small size to other faces. Further it has been shown that the structural planes of highest reticulate atomic density will grow slowest. In gypsum this rule generally applies since the structural plane of highest reticulate density is the cleavage plane or clinopinacoid (010), and the gypsum crystals showing this as a prominent face are extremely common.

As has been pointed out, the gypsum crystals found in the muds of Great Salt Lake grow so that their flattened shape, which is not parallel to (010), is transverse to the bedding of the mud. If we assume that the water-saturated muddy material allowed free physical growth of the crystal, and that the fine character of the mud did not permit an active preferred direction of feeding solution movement, then the uncommon shape of these crystals is probably due to an unusual chemical environment. How the bacteria are related to this habit of crystal growth is not known.

In the shales that contain gypsum the crystals are generally flattened along (010). Judging from the selenite crystals collected in shale by the writers this plane lies parallel or sub-parallel to the bedding. In the compaction and consolidation of a water-saturated clay the vertical pressure on an inclosed crystal will exceed the horizontal. Since the gypsum crystals in the Great Salt Lake clays grow transverse to the bedding, then the greater vertical pressure upon compaction would cause the crystal to dissolve on the knife-like edges and to grow normal

to the compression direction, and parallel to the "relief" direction. If (010) in the vertical crystal is horizontal, as it may be, then the crystal will be transformed so as to lie flat in the plane of bedding.

Probably many selenite crystals found in shale or on shale erosion surfaces have been involved in plastic flow incident to deformation of the shale. Their crystal form in this event would reflect a metamorphism in addition to any change in habit that occurred during compaction.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 22, NO. 4, PP. 239–240
FIG. 1, DECEMBER, 1952

NOTE

AN OCCURRENCE OF ARTIFICIAL OÖLITES

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In the course of fruit tree rooting experiments at the University of Miami, a rooting medium was chosen which had free draining and aeration properties. During a report on the experimental work which was presented before the annual meeting of the Florida State Horticultural Society in 1950 at Winter Haven, Florida, (Ochse and Reark, 1950), it was brought to the author's attention that the medium used and recommended was composed of artificial oölites, and a description of the oölites and conditions of formation was requested by Doctor W. H. Twenhofel.[1]

The United States Navy operates wells and a pumping station at Florida City, Florida (on U. S. Highway No. 1, a short distance south of Homestead, Florida), from which water is conducted to the Key West Naval Base. The underground water of southern Florida is rather hard due to percolation through limestones, and that at the pumping station is rather consistently near 180 ppm of solid matter of which most is calcium bicarbonate, $Ca(HCO_3)_2$. Inasmuch as the aqueduct is considerably over 100 miles long and the water is primarily to be used for naval operation, including boilers, elaborate measures are taken to lower the content of precipitable salts, thus lessening scale-formation. The water softening method employs quicklime and a zeolite, the former to cause the reaction $Ca(HCO_3)_2+Ca(OH)_2=2CaCO_3+2H_2O$ and the latter as a base exchange material. Tri-sodium phosphate is metered into the water in advance of treatment as a retarding agent as the practically instantaneous reaction would otherwise clog the nozzle which conducts the water from the main to the spiractor (spiral reactor) in which the exchange takes place. The resulting water has its salt content lowered to about 35 ppm and the pH has become 9.4, that is, it is still strongly alkaline.

The zeolite particles used have an irregular shape that is roughly rectangular. The dimensions average about 0.3 mm along the long axis and about 0.15 along the shorter axis. The material is bagged and shipped from New Jersey mines (seems to be New Jersey glauconite, W.H.T.). The oölites build up around the zeolites as a series of concentric shells, the form at first being ovate spheroidal to conform with the nuclear zeolite particles, but they later become spherical, or nearly so, because of the constant rotation of the spiractor. There is no information available as to the rate of formation of the shells or the reason for the formation of the shells, as the operation is a continuous one. The shells vary in thickness with the average about 0.05 mm and they are opaque. Cleavage tends to be at right angles to the plane of the tangent and separation of shell from shell is not noticeable (fig. 1).

Formerly the spiractor was allowed to run for six months or more without replacement of zeolites and the resulting oölites ranged in dimensions from 0.6 mm to over 10 mm and averaged about 3 mm. The spiractor is now cleaned every six weeks and the oölites formed under

[1] I heard this paper presented and was struck by the fact that oölite formation seems to be proceeding on a considerable scale under conditions showing conditions of formation. I considered the information of sedimentational importance and requested Mr. Reark, who presented the paper of the rooting methods, to prepare a manuscript describing the oölites. —W. H. Twenhofel.

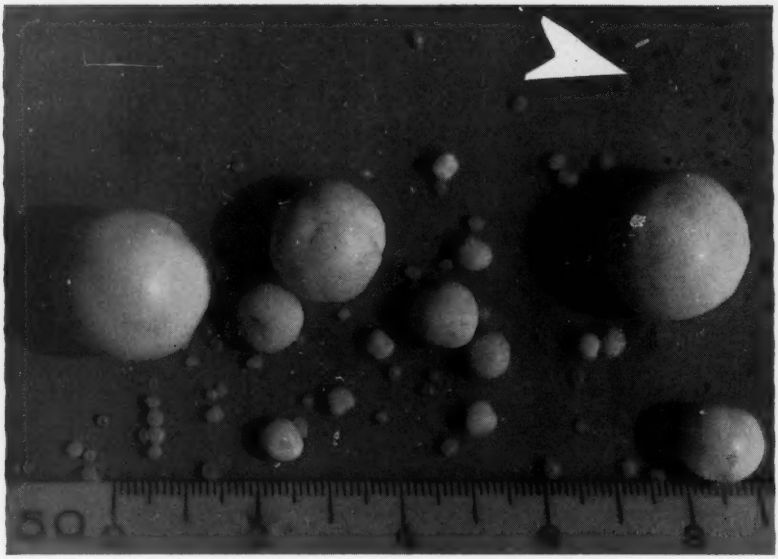

FIG. 1.—Artificial oölites formed by the water softening process at the U.S. Navy water station, Florida City. Arrow points to zeolite particles around which the oölites form. Scale in inches, each division 1/50th in.

these conditions average in dimension about 0.6 mm with a variation of about ±0.1 mm. Under the conditions of formation dimensions of oölites are obviously related to time.

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DECEMBER, 1952

ANNOUNCEMENTS

ADVISORY COMMITTEE ON RADIOACTIVE MINERAL EXPLORATION

On June 5, at Denver, Colorado, delegates appointed by the presidents of A.A.P.G., S.E.G., and S.E.P.M. organized a committee to be known as the "Advisory Committee on Radioactive Mineral Exploration." This committee is jointly sponsored by the three societies above named. The following statement, called "Circular 1," was drawn up at the Denver meeting:

SEARCHING FOR RADIOACTIVE MINERALS IN ROUTINE EXPLORATION FOR OIL AND GAS

1. *Urgency for expanded exploration for radioactive minerals in the United States.*—In view of the increasing importance of radioactive minerals, and in particular of uranium ores, as a source of atomic energy, expecially for purposes of national defense, it is urgent that no opportunity be overlooked or neglected for widespread alertness for evidences of such minerals. Not only is there need for discovering more occurrences of these minerals, but also there is need for more information on their distribution in areas where they are already known to be present.

2. *Coincidence of areas explored for petroleum and areas prospective for uranium ores.*—It so happens that in many regions where oil and gas are sought, ores of uranium may occur. This is especially true of extensive areas in the Rocky Mountain Province and in the western part of the Central Plains Province. There are many deposits of carnotite (a common uranium ore) in the Plateau Province of southeastern Utah and the adjoining corners of Colorado, New Mexico, and Arizona, and recently deposits of uranium minerals have been found in the Powder River Basin in Wyoming. In these same areas, and in many others where uranium ores *may* occur, exploration for petroleum is being carried on aggressively by numerous companies. Therefore, it is suggested that these companies be encouraged to take steps to combine with their petroleum exploration a moderate effort at exploration for radioactive minerals.

3. *Advisory Committee on Radioactive Mineral Exploration.*—Within the membership of the American Association of Petroleum Geologists (A.A.P.G.), the Society of Exploration Geophysicists (S.E.G.), and the Society of Economic Paleontologists and Mineralogists (S.E.P.M.), a committee has been organized, to be known as the Advisory Committee on Radioactive Mineral Exploration.

4. *Functions and Policies of the Committee.*—This committee, as its name implies, will serve only in an advisory capacity. Its primary functions are:

a. To invite those who may be inclined or interested, to investigate the feasibility of their carrying on exploration for radioactive minerals along with their petroleum exploratory efforts;

b. To give advice as to how and where such exploration for radioactive minerals may be conducted, if desired;

c. To advise where information can be obtained concerning the search for radioactive materials;

d. To endeavor to keep abreast of what is going on in this search for radioactive materials; and

e. To encourage the preparation and presentation of papers on the subject of exploring for useful radioactive minerals.

This committee will concern itself with over-all encouragement of participation of the oil and gas industry in exploration for radioactive minerals and will deal with the broad aspects and policies of such a relationship. It will not be too much concerned with detailed techniques, problems of instrumentation, methods,

and processes for detailed surveys, nor with any of the technical aspects of the program which may better be handled by specialists. In no way will it suggest unified cooperation, or cooperative procedure, between organizations for the conduct of radioactive mineral exploration. Its whole objective is to stimulate an interest in the search for radioactive minerals, occurring within feasible mining depths, when and where petroleum exploration is in progress.

5. *Suggestions regarding radioactive mineral exploration.*—The oil companies, consulting firms, and others engaged in petroleum exploration can function in exploring for radioactive minerals:

(a) by observations with Geiger counter on outcrops where surface mapping is in progress;

(b) by holding out, for special study, those gamma-ray logs which reveal "kicks" stronger than the normal "kicks" known to be associated with the Chattanooga shale or similar highly radioactive shales;

(c) by Geiger-counter or scintillation-counter examination of cuttings from seismic shot holes; and

(d) by similar examination of the cuttings from approximately the upper 500 feet of holes drilled for oil or gas or drilled as exploratory core holes, "slim holes." or "stratigraphic test holes."

(A few remarks may be made here on paragraphs (b), (c), and (d) under 5. When gamma-ray logs show abnormally high "kicks," they may be indicating the presence of radioactive ores at depths too great for exploitation. Such logs may be of value either (1) where they reveal high radioactivity in formations known to be highly radioactive at or near their outcrop, because this suggests wide distribution of such radioactivity, or (2) where by revealing high radioactivity at considerable depths, they suggest that search should be made for indications of similar high radioactivity in the same formations at or near the outcrop of these formations.

Under present prices and conditions, 500 feet is probably as deep as uranium mineral can be profitably mined; hence the mention of 500 feet in 5 (d).)

6. *Utilization of evidences of radioactive minerals.*—If and when evidences of possible economic radioactive minerals is found, the discoverer is free to determine his own course of action. If desired, he could investigate the possibility of mining on his own account; or he could sell his rights, probably on a royalty basis to some outside mining concern.

7. *Conclusion.*—On the basis of the foregoing, the committee suggests that those engaged in petroleum exploration carefully consider including, in the course of their normal exploration activities, their own program of prospecting for radioactive minerals.

Additional information can be obtained by writing to the chairman of the committee, Dr. Frederic H. Lahee, Sun Oil Co., Box 2880, Dallas, Texas.

The membership of the Advisory Committee on Radioactive Mineral Exploration is as follows:

Frederic H. Lahee, *Chairman*
Henry C. Cortes, *Vice-Chairman*
John Emery Adams
John G. Bartram
Cecil H. Green
Sigmund Hammer
Gerhard Herzog
Morton T. Higgs
J. Harlan Johnson
A. I. Levorsen
Clarence L. Moody
Robert R. Rieke
Wilfred B. Tapper
Gerald H. Westby

The committee will be glad to endeavor to answer questions and give advice within the scope of its functions, as outlined in section four of Circular 1.

JOINT ANNUAL MEETING SOCETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS SOCIETY OF ECONOMIC GEOLOGISTS

Sam Houston Coliseum, Houston, Texas, March 23–26, 1953

The joint annual meeting of the three societies will be held at the Sam Houston Coliseum, Houston, Texas, on March 23, 24, 25, and 26, 1953.

A call for papers to be presented at the annual S.E.P.M. meetings has been issued by Morton B. Stephenson, Vice-President of S.E.P.M., who is working on the technical program. Members planning to submit papers should notify Mr. Stephenson, P.O. Box 3092, Houston, Texas, in the near future, of their titles and length of time desired for presentation. Abstracts, typewritten, double-spaced, and in duplicate, are due on January 1, 1953.

Notices regarding housing and requests for reservations for accommodations have been mailed to members and have been published in the *Bulletin of the American Association of Petroleum Geologists*, vol. 36, no. 10, October, 1952, pp. 2062, 2063.

ANNUAL AWARD FOR OUTSTANDING PAPER PUBLISHED IN THE JOURNAL OF SEDIMENTARY PETROLOGY: MEMBERS OF S.E.P.M. TO SELECT PAPER

The Society of Economic Paleontologists and Mineralogists is establishing annual awards, one for the most outstanding paper in the *Journal of Sedimentary Petrology* and one for the most outstanding paper in the *Journal of Paleontology*. The awards will be in the form of a scroll of commendation. It is believed that these awards will encourage research in the fields of interest to Society members by providing a concrete record of achievement. No limitation is placed on the age or society affiliations of the recipients. The awards will be granted for papers published during the second prior year to the year of award. This will provide ample time for assessing the value of a contribution; the first two awards to be granted at the 1953 annual meeting at Houston will cover the issues published in 1951.

The members of the Society are the best judges of the quality of contributions in their fields, and the sole basis for awards will be voting by the membership. Each member and associate member of the Society of Economic Paleontologists and Mineralogists is entitled to vote for one paper in each *Journal:* however, because the ballots are made available only by publication in the *Journals*, voting will be limited by availability of ballots, which in general will be determined by whether the member subscribes to one or to both *Journals*.

The ballot for the most outstanding paper in the *Journal of Sedimentary Petrology* in 1951 is printed in the current (December, 1952) issue. Ballots for papers published in the *Journal of Sedimentary Petrology* may be sent to the Editor, who will forward them to the Research Committee. The Research Committee will count the ballots and designate the recipient of the award.

The significance and importance of the awards will depend on the response of the members of the Society. Your ballot will focus attention on the paper and the field of research which you believe to be most valuable and promising. The awards will encourage and may facilitate further research by the recipients in particular and also by the Society as a whole. The results of the balloting may further serve as a partial guide to the editor in determining the future content of the *Journal*.

Because the symposium, "Turbidity

currents and the transportation of coarse sediments to deep water" was published during 1951, as S.E.P.M. Special Publication No. 2, the papers of this symposium may be included with the regular *Journal of Sedimentary Petrology* papers of Volume 21 (1951) in the competition for the award.

The ballot printed below should be detached and used only by members and associate members of S.E.P.M. The voter's membership in the Society must be proved either by his signature of the ballot or by his signing an envelope marked "annual award ballot," in which the unsigned ballot is enclosed. In either case, the voter's identity will be kept confidential by the Research Committee. The ballot must be received at the editorial office of the *Journal of Sedimentary Petrology* not later than February 15, 1953.

BALLOT FOR ANNUAL AWARD

For outstanding paper published in the JOURNAL OF SEDIMENTARY PETROLOGY during the year 1951 (Volume 21) or in S.E.P.M. SPECIAL PUBLICATION NO. 2, 1951, symposium, "Turbidity currents and the transportation of coarse sediments to deep water."

The outstanding paper was: Author _____

Title _____

I recommend it for the annual award of the S.E.P.M.

(Signed) _____
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Mail ballot to:

J. L. Hough
Journal of Sedimentary Petrology
Department of Geology
University of Illinois
Urbana, Illinois

Ballots will be counted by the S.E.P.M. Research Committee; Henry W. Menard Chairman.

Ballot must be received at the above address not later than Feb. 15, 1953.

Journal of Sedimentary Petrology

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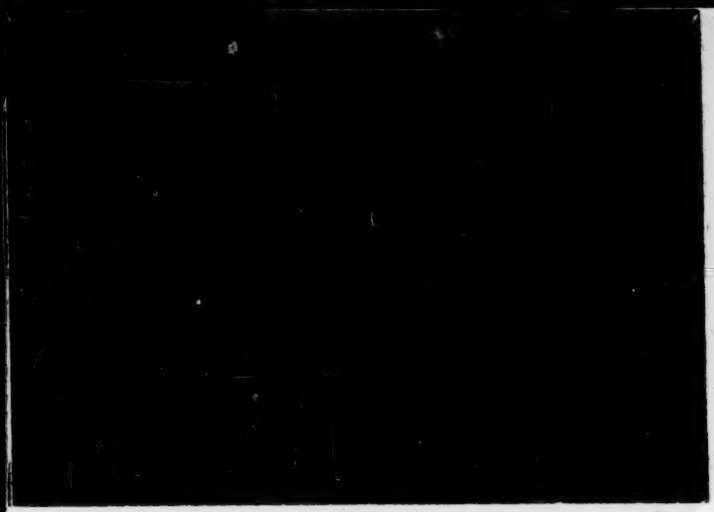

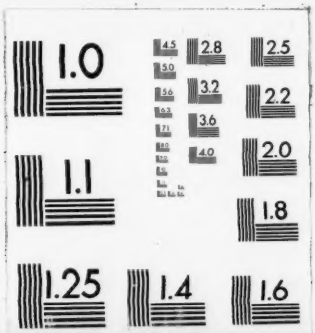
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